GEOPHYSICS

VOL. XXV, NO. 1 FEBRUARY, 1960

Silver Anniversary

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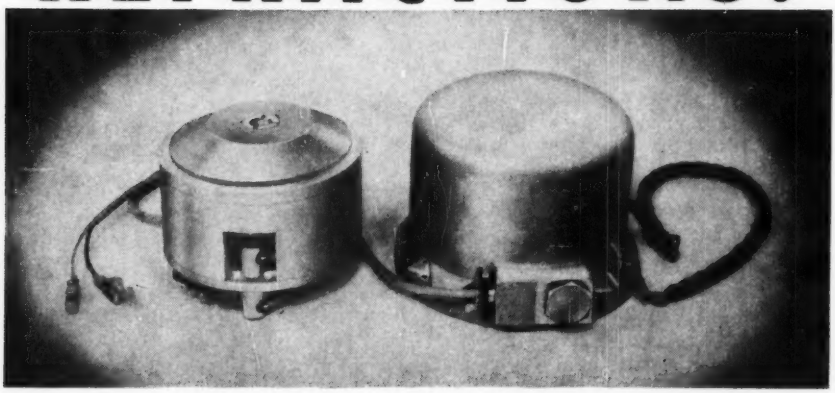

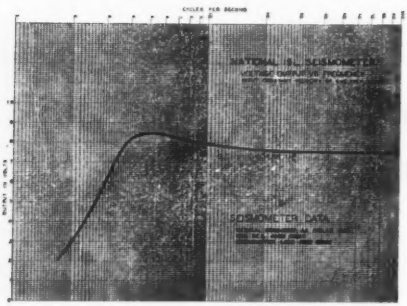

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Published by George Banta Company, Inc., Menasha, Wisconsin. Issued six times a year in February, April, June, August, October and December. Second-class postage paid at the Post Office at MENASHA, WISCONSIN, under the Act of March 3, 1879. Acceptance for mailing at the special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, Section 538, P. L. & R., authorized March 19, 1941.

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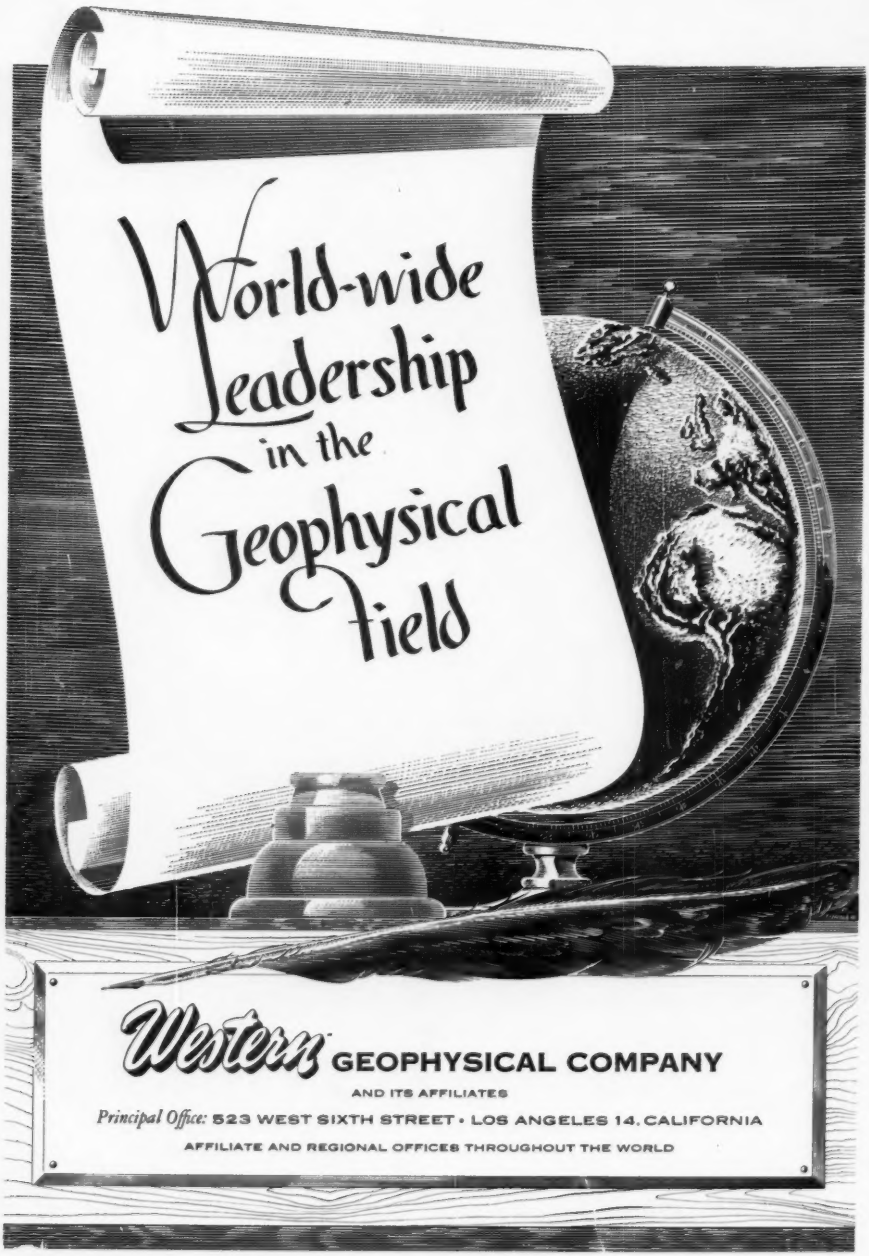
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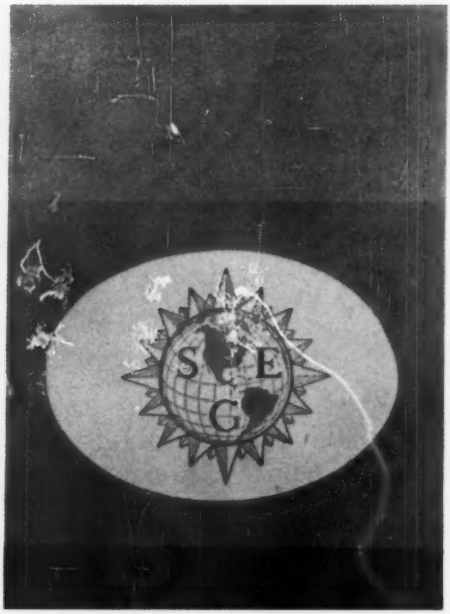

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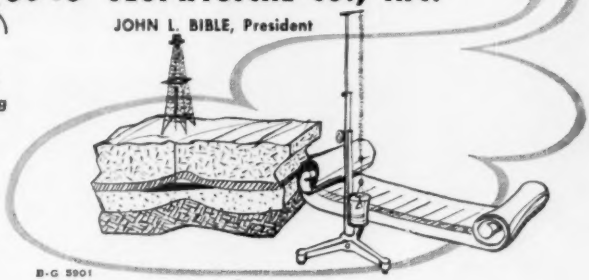

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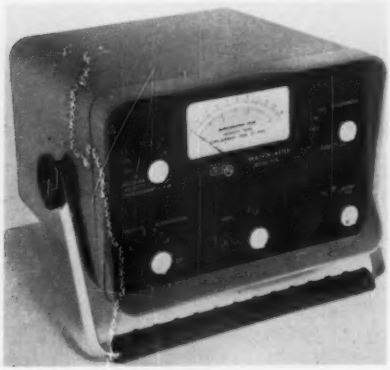

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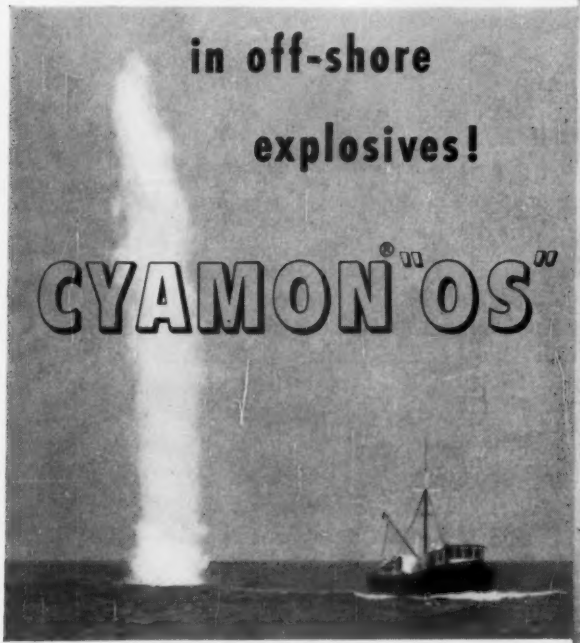

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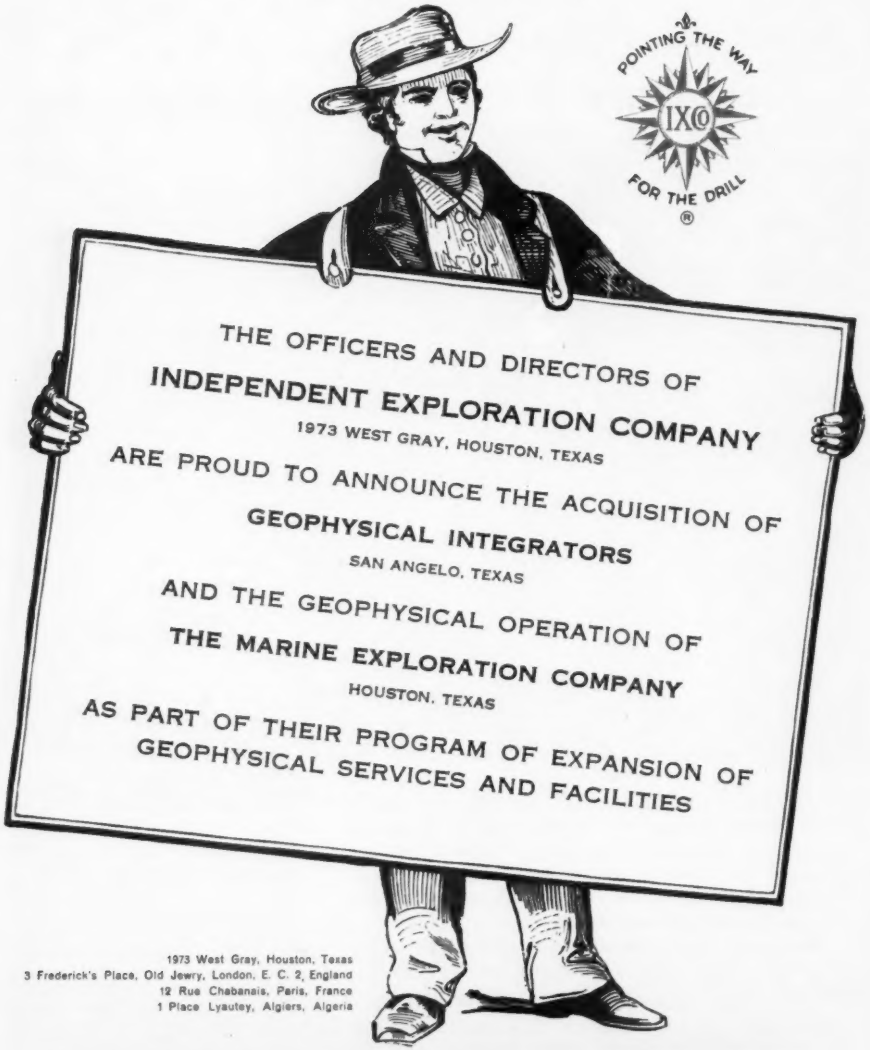

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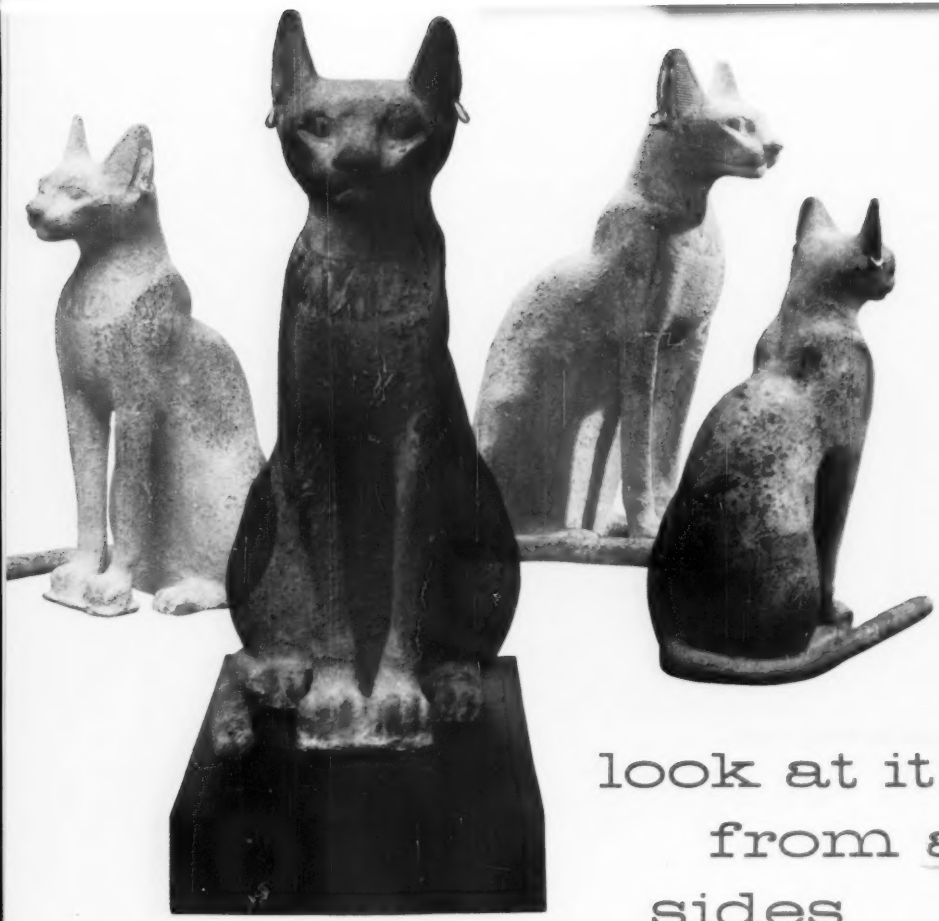

look at it from all sides

If you're accustomed to looking at cats head on, you're missing much that is feline. If you're used to looking at all things in only one way, you're perhaps missing much that is good. If you look at the GAI-GMX group as being given only to interpretation, you are dead wrong. Not only does GAI-GMX operate field crews whose work is done with total seriousness of purpose, but these crews operate all over the world. Right now they are busy in the Near East, Canada, South America, and the USA. The interpretation of these data is done with an attention to detail which gives you the most from your exploration dollar. Gravity, magnetic, and seismic surveys from anywhere in the world are translated into detailed interpretations of underlying geologic structures. Geophysical exploration is so costly that today you can afford only the best.

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Dr. L. L. Nettleton
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The Goddess Bastet, Egyptian, Ptolemaic Period, Courtesy of The Metropolitan Museum of Art, funds from various donors.

VOLUME XXV FEBRUARY, 1960 NUMBER 1

GEOPHYSICS

EDITORIAL

THE SILVER ANNIVERSARY OF *GEOPHYSICS*

The twenty-fifth volume inaugurates the bi-monthly publication of GEOPHYSICS. Prior to the founding of GEOPHYSICS, a one-number volume entitled *The Journal of the Society of Petroleum Geophysicists* was published in 1935. Our Silver Anniversary issue thus celebrates the realization of Volume XXV of GEOPHYSICS and the initiation of the second quarter-century of our publications. It is appropriate, therefore, that we include the historical and the significantly new.

Naturally the historical portion of this issue features our authors and our Editors. *Classics of GEOPHYSICS* selects the papers and authors of "acknowledged excellence." A special section is devoted to our Editors, their staffs, and others who have played important roles in our publications. That section contains a tribute to the one man who has been intimately associated with the production of every issue of GEOPHYSICS. In addition to preserving the record, the Editors' Section was designed to honor the first ten Editors of GEOPHYSICS who by their efforts, unaided by the full-time services of the Editorial Assistant first available to the eleventh Editor, imparted to GEOPHYSICS its character and were responsible in great measure for its reputation.

The final paper in the historical portion of this issue is a review of the development of geophysical instrumentation (W. T. Born) which should be of particular value to younger geophysicists.

There is cause for pride in the group of technical papers, covering every major field of geophysics, contained in this issue. It speaks well for the virility of our science when one issue however special, can include papers on a new seismic method (Crawford, Doty, and Lee), successful tests of a new instrument (Nettleton, La Coste and Harrison), a new exploration method (Dunlap et al), and a new theory (Sato and Mooney). Talwani and Ewing, Lindsey, Wuenschel, and Musgrave et al, use as a matter of course in their outstanding contributions, techniques barely recognized a decade ago. White and Press relate present trends in research. Pickett describes a major refinement in the interpretation of acoustic logs. Last and far from least, Graebner presents a noteworthy modern exploration-type paper. We believe that every technical paper in this issue eventually will receive the accolade of *classic*.

While justifiably proud of our past record, the evidence in our Silver Anniversary issue suggests that our greatest achievements lie ahead.

The Editor

Museum of Art, funds from various donors.

CLASSICS OF *GEOPHYSICS**

THE EDITOR

ABSTRACT

The nominations of 32 judges for *Classic Papers* of GEOPHYSICS selected 46 *classics* including 35 seismic papers, four gravity and magnetic, three electrical, and four well-logging. The term classic is used in the sense of "a work of the highest class and of acknowledged excellence, or its author." Eighty-seven *Classic Authors* were selected.

A study of the significance of these selections reveals that the immediate future promises spectacular achievements.

INTRODUCTION

GEOPHYSICS has published 799 formal technical papers among the thousand papers and communications appearing in its first 24 volumes. All had passed the careful scrutiny of the Editors and the referees as to the value, clarity, and suitability of their contents. The contribution of GEOPHYSICS is the totality of these papers of a high standard of excellence perpetually available for reference. No higher honor can be offered to the authors of these papers than this service, already performed.

The celebration of the Silver Anniversary of GEOPHYSICS would be meaningless however if we failed to salute those especially meritorious papers and their authors which have made our journal great.

While all of the papers met a high standard, some of them by their relative timeliness, by their special contributions, or by their over-all excellence are deserving of special recognition. Dr. Milton Dobrin suggested that the "Classic Papers" of GEOPHYSICS be selected for listing and discussion in this Silver Anniversary issue. Webster's New International Dictionary defines the noun *classic* as: "a work of the highest class and of acknowledged excellence, or its author." We shall use the term *classic*, either as a noun or an adjective, within essentially this frame of reference. The following sections describe the procedures used for selecting *classic papers* and *classic authors* of GEOPHYSICS and contain some discussion of the significance of these selections.

METHOD OF SELECTION OF CLASSICS OF *GEOPHYSICS*

A group of 65 members of SEG selected with consideration of their judgment, special interests, and technical ability received the following letter:

April 20, 1959

The Silver Anniversary Issue of GEOPHYSICS, February 1960, Volume XXV No. 1 was planned to contain an article entitled "Classic Papers of GEOPHYSICS." Due to circumstances including transfer to a foreign country, the person who had accepted the responsibility for undertaking this project will be unable to proceed with his task.

* Manuscript filed August 24, 1959.

As an emergency measure I am writing you as one of sixty from whom I wish to solicit nominations for papers published in GEOPHYSICS from 1936 to date which could be termed "Classic Papers." We shall use this term in the broad sense of papers to which frequent references are made, pioneer papers on important subjects, and papers which for any reason are considered especially significant.

Since this is not a prize award there is no limit placed on the number of papers so nominated. Naturally each judge will make his selections from those fields wherein he believes he is competent to decide.

After your answers are received it is my intention to seek an author or authors for the paper.

Some comments from you concerning the reasons for your nominations would be helpful to the authors but is not mandatory.

I am hopeful that my request is not imposing too great a time burden on you. I am inclined to believe that a scanning of the Volume Contents of each volume would be sufficient to recall to your mind those papers which possibly unconsciously, you have already selected as significant.

Thanking you for your cooperation.

Very truly yours,
L. Y. FAUST, Editor.

Thirty-two responses within a three month period form the basis of judgment for the selection of *classics* of GEOPHYSICS. The names of those responding are listed under *Acknowledgments*.

Judges' Nominations

As might be expected from a request made purposefully general, there was considerable variation in the nature of the responses. One judge nominated only one paper which, he stated, should be republished in this issue. The other extreme was 127 nominations. A total of 911 nominations were received for 291 papers. Thus, the average number of nominations by each judge was 28.

One judge nominated "all Best Paper Awards" in addition to other specific selections. Some excluded Best Paper Awards, presumably on the principle that they had been sufficiently honored. One wrote that he had imposed a limit of no more than one paper from any volume. Another reviewed every paper in GEOPHYSICS before making his selections.

A few judges volunteered nominations from the precursors of GEOPHYSICS. These are included as "Some Outstanding Papers" in the write-up of the Editors of these early volumes on pages 16–18 of this issue.

Dr. Irwin Roman stated, "One conclusion reached during my review has been that GEOPHYSICS has published many papers of high quality and lasting value." The response of most of the panel confirmed that judgment.

Mechanics of Selection of Classics

A master list of the judges' nominations permitted the tabulation by category and by volume (year) of total nominations for each paper. Thirty judges nomi-

nated seismic papers, 24 nominated gravity and magnetic papers, 19 considered electrical methods and 12 were interested in well-logging.

One nomination of a paper as a classic should mark that paper as outstanding. Two independent nominations certainly describe it as distinguished. We have accordingly listed all papers receiving two or more nominations as *Distinguished Papers* in the pages of this issue devoted to the Editors of GEOPHYSICS (p. 25–55). A total of 162 papers are so classified.

Not all judges made their selections from a consideration of the 23 complete volumes and the first two numbers of Volume XXIV issued prior to the letter of solicitation. One judge stated that his seismic selections were confined to the first two volumes only, since his sphere of interest had shifted subsequently. Some judges stated that no papers later than Volume XVIII, 1953 had been considered. Others made it evident that the later issues were not reviewed. The last issue from which a paper was nominated could not, by itself, be taken as evidence that later volumes were not reviewed since the absence of nominations could represent a considered judgment. On the other hand the "negative vote" of the judges was not permitted for those years wherein the evidence[1] indicated that judgment had been suspended.

Some judges displayed diffidence by failing to nominate their own contributions. Other judges begged the question by stopping their nominations at the volume prior to the appearance of one of their own important papers. A few judges exhibited the praiseworthy objectivity of nominating one or more of their own papers. To equalize the judgments a nomination for his paper was added automatically to each judges' list when it was nominated only by other judges. The validity of this decision seems evident. As a check, however, several judges were requested to permit the Editor to make these additions to their lists. Their reactions indicated the fairness of this procedure.

Aside from these editorial manipulations there was no attempt to read the judge's mind. If a judge nominated only Part I of a paper published in two or more parts the author was given credit only for that nomination. The selections of the judge limiting his nominations to a maximum of one per volume were accepted as such despite this disagreement with the general principles stated in the letter of solicitation.

The nominations of the judges and all the tabulations of the data have been placed in the Editorial Files and transmitted to Dr. Nelson C. Steenland, the succeeding Editor. They will be available to anyone qualified to study the wealth of material contained therein.

The tabulation procedure permitted the comparison of the total nominations for each paper against the total number of judges active in that category for that volume and year. Those papers receiving nominations from twenty-five

[1] An example of such evidence is the case of one judge who nominated through Volume XXI, skipped Volume XXII and nominated a paper appearing in Volume XXIII but who referred only to its presentation at one of our Annual Meetings.

percent were given the title of *classic*. The rule was applied rigidly with the further qualification that regardless of the number of judges a minimum of three nominations was necessary. This latter requirement became the dominant figure only in the case of the well-logging category after Volume XXI.

The imposition of the twenty-five percent requirement is arguable. Considering the diversity of interest and emphasis of the judges within each category and the fact that these were open nominations—not votes for a pre-selected list of candidates—the requirement seems sufficiently high. When it is realized that independent nominations by seven judges in the seismic category or five in gravity and magnetics would fail to qualify as *classic* a paper appearing before 1954, the requirement appears overly stringent.

A total of 722 nominations for 196 papers in the seismic field selected 35 *classics*. One hundred nominations for gravity and magnetic papers, distributed over 47 papers named only four *classics*. Sixty-seven nominations in the electrical group for 37 papers determined three *classics*. Twenty-one well-logging nominations for nine papers selected four.

Classic Papers of *GEOPHYSICS*

The decision of the judges as interpreted by the Editor confers the title of CLASSIC in the sense of "a work of the highest class and of acknowledged excellence" on the following papers listed in four categories and in approximate order of selectio within each group:

CLASSIC PAPERS OF *GEOPHYSICS*

SEISMIC

THE FORM AND NATURE OF SEISMIC WAVES AND THE STRUCTURE OF SEISMOGRAMS
Norman Ricker, 1940

A NEW REFLECTION SYSTEM WITH CONTROLLED DIRECTIONAL SENSITIVITY
F. Rieber, 1936

THE SYNTHESIS OF SEISMOGRAMS FROM WELL LOG DATA
R. A. Peterson, W. R. Fillippone, and F. B. Coker, 1955

THE PRODUCTION OF ELASTIC WAVES BY EXPLOSION PRESSURES, PART I. THEORY AND EMPIRICAL FIELD OBSERVATIONS
Joseph A. Sharpe, 1942

CONTINUOUS VELOCITY LOGGING
G. C. Summers and R. A. Broding, 1952

REFLECTION AND TRANSMISSION COEFFICIENTS FOR PLANE WAVES IN ELASTIC MEDIA
M. Muskat and M. W. Meres, 1940

ATTENUATION OF SHEAR AND COMPRESSIONAL WAVES IN PIERRE SHALE
F. J. McDonal, F. A. Angona, R. L. Mills, R. L. Sengbush, R. G. Van Nostrand, and J. E. White, 1958

THE ATTENUATION CONSTANT OF EARTH MATERIALS
W. T. Born, 1941

GHOST REFLECTIONS CAUSED BY ENERGY INITIALLY REFLECTED ABOVE THE LEVEL OF THE SHOT
F. A. Van Melle and K. R. Weatherburn, 1953

ON SEISMIC COMPUTATIONS WITH APPLICATIONS I
M. M. Slotnick, 1936

A VELOCITY FUNCTION INCLUDING LITHOLOGIC VARIATION
L. Y. Faust, 1953

WAVELET CONTRACTION, WAVELET EXPANSION, AND THE CONTROL OF SEISMIC RESOLUTION
Norman Ricker, 1953

THE FORM AND LAWS OF PROPAGATION OF SEISMIC WAVELETS
Norman Ricker, 1953

SEISMIC VELOCITY AS A FUNCTION OF DEPTH AND GEOLOGIC TIME
L. Y. Faust, 1951

ON SEISMIC COMPUTATIONS WITH APPLICATIONS II
M. M. Slotnick, 1936

ELASTIC WAVE VELOCITIES IN HETEROGENEOUS AND POROUS MEDIA
M. R. J. Wyllie, A. R. Gregory, and L. W. Gardner, 1956

COMPOSITION OF REFLECTIONS
J. P. Woods, 1956

SEISMIC RECORD SECTIONS
H. R. Prescott, 1951

THE PRODUCTION OF ELASTIC WAVES BY EXPLOSION PRESSURES, PART II. RESULTS OF OBSERVATIONS NEAR AN EXPLODING CHARGE
Joseph A. Sharpe, 1942

A SEISMIC VELOCITY LOGGING METHOD
C. B. Vogel, 1952

TWO-DIMENSIONAL MODEL SEISMOLOGY
Jack Oliver, Frank Press, and Maurice Ewing, 1954

COMPLEX REFLECTION PATTERNS AND THEIR GEOLOGIC SOURCES
F. Rieber, 1937

ELASTIC WAVES THROUGH A PACKING OF SPHERES
Fritz Gassmann, 1951

SEISMIC REFLECTION RECORDS OBTAINED BY DROPPING A WEIGHT
Edwin B. Neitzel, 1958

DETECTION OF REFLECTIONS ON SEISMIC RECORDS BY LINEAR OPERATORS
G. P. Wadsworth, E. A. Robinson, J. B. Bryan and P. M. Hurley,1953

THE POULTER SEISMIC METHOD OF GEOPHYSICAL EXPLORATION
Thomas C. Poulter, 1950

THE SIGNIFICANCE OF DIFFRACTION IN THE INVESTIGATION OF FAULTS
Theodor Krey, 1952

PREDICTIVE DECOMPOSITION OF SEISMIC TRACES
Enders A. Robinson, 1957

VELOCITY DETERMINATIONS BY MEANS OF REFLECTION PROFILES
C. H. Green, 1938

VISUAL PRESENTATION OF ELASTIC WAVE PATTERNS UNDER VARIOUS STRUCTURAL CONDITIONS
F. Rieber, 1936

WATER REVERBERATIONS—THEIR NATURE AND ELIMINATION
M. M. Backus, 1959

A THREE-DIMENSIONAL SEISMIC WAVE MODEL WITH BOTH ELECTRICAL AND VISUAL OBSERVATION OF WAVES
J. F. Evans, C. F. Hadley, J. D. Eisler, and D. Silverman, 1954

THE MOVEOUT FILTER
Carl H. Savit, John T. Brustad, and Joseph Sider, 1958

REFLECTIONS FROM MULTIPLE TRANSITION LAYERS. PART I—THEORETICAL RESULTS
L. H. Berryman, P. L. Goupillaud and K. H. Waters, 1958

DIRECTIVITY EFFECT OF ELONGATED CHARGES
A. W. Musgrave, G. W. Ehlert and D. M. Nash, Jr., 1958

GRAVITY AND MAGNETIC

THE DIRECT APPROACH TO MAGNETIC INTERPRETATION AND ITS PRACTICAL APPLICATION
Leo J. Peters, 1949

TERRAIN CORRECTIONS FOR GRAVIMETER STATIONS
Sigmund Hammer, 1939

THE GULF AIRBORNE MAGNETOMETER
R. D. Wyckoff, 1948

THE SECOND DERIVATIVE METHOD OF GRAVITY INTERPRETATION
Thomas A. Elkins, 1951

ELECTRICAL METHODS

BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING
Louis Cagniard, 1953

GEOPHYSICAL EXPLORATION BY TELLURIC CURRENTS WITH SPECIAL REFERENCE TO A SURVEY OF THE HAYNESVILLE DOME, WOOD COUNTY, TEXAS
Eric Boissonnas and Eugene C. Leonardon, 1948

PROSPECTING FOR GROUND WATER BY INDUCED ELECTRICAL POLARIZATION
Victor Vacquier, Charles R. Holmes, Paul P. Kintzinger and Michel Lavergne, 1957

WELL-LOGGING

GAMMA-RAY WELL-LOGGING
Lynn G. Howell and Alex Frosh, 1939

FLUID SATURATION OF ROCKS FROM VELOCITY LOGS
W. G. Hicks and J. E. Berry, 1956

NEUTRON LOGGING OF DRILL HOLES: THE NEUTRON-NEUTRON METHOD
C. W. Tittle, Henry Faul, and Clark Goodman, 1951

LOGGING OF DRILL HOLES BY THE NEUTRON, GAMMA METHOD AND GAMMA RAY SCATTERING
Henry Faul and C. W. Tittle, 1951

Conspicuously absent from this list are such papers as Wyckoff's *The Gulf Gravimeter* (1941), Muffly's *Airborne Magnetometer* (1946), Evjen's *Vertical Gradient in Gravitational Interpretation* (1936). All barely failed to qualify as did the papers of Maillet on *The Fundamental Equations of Electrical Prospecting* (1947) and of Pritchett on *Attenuation of Radio Frequency Waves* (1952). In the seismic group the absence of the Frank and Doty paper, *Signal to Noise Ratio Improvements by Filtering and Mixing* (1953), the Loper and Pittman paper, *Seismic Recording on Magnetic Tape* (1954), E. M. Palmer's *The Gulf Seismic Profile Printer* (1957) and Quarles' *Fault Interpretation from Seismic Data in Southwest Texas* (1950) are other examples of excellent papers barely failing to qualify because of too rigid selection. We have named these papers because we believe that these too are *classics* and that our system was at fault.

CLASSIC AUTHORS OF *GEOPHYSICS*

The definition of *classic* as cited, applies also to authors. Some of our most respected geophysicists are known for several of their significant works rather than for a single outstanding contribution. As might be expected therefore, the nominations for their papers were distributed according to the special interests of the judges.

The selection of CLASSIC AUTHORS OF *GEOPHYSICS* was based on the total number of nominations received by the author. The same procedure as for *Classic Papers* governed their selection. In determining the order, however, a compromise was used between order based on percentages and order based on total number of nominations. Full credit was given to each of the joint authors of a paper. All authors are of necessity grouped in a single list since many authors have contributed important papers to more than one branch of geophysics. Following the name of each author is listed the year of publication of the papers nominated. When two or more of his papers appearing in the same year received nominations that information is supplied by the figure in parenthesis following the year. For completeness the volunteer nominations of the judges of papers published prior to GEOPHYSICS are included but each early paper nominated is given credit, somewhat arbitrarily, for a single nomination. Where joint authors shared all of their nominations in common, they are grouped together. We submit the following list of those who have been honored with the title.

CLASSIC AUTHORS OF *GEOPHYSICS*

NORMAN RICKER, 1940, 1941, 1944, 1950, 1953 (2)
F. RIEBER, 1936 (2), 1937
FRANK PRESS, 1948, 1950, 1951 (2), 1954 (3), 1956, 1957
JOSEPH A. SHARPE, 1942 (2), 1944, 1952
MAURICE EWING, 1948, 1950, 1951 (2), 1954 (3), 1955
M. M. SLOTNICK, 1932, 1936 (3), 1950
M. MUSKAT, 1937, 1940 (2), 1941
L. Y. FAUST, 1935, 1951, 1953
M. W. MERES, 1940 (2)
W. T. BORN, 1935, 1941 (2)
L. W. GARDNER, 1939, 1947, 1949, 1956
R. A. PETERSON, W. R. FILLIPPONE, and F. B. COKER, 1955
R. A. BRODING, 1952 (2)
R. G. VAN NOSTRAND, 1953, 1954 (2), 1955, 1958
R. L. SENGBUSH, 1954, 1958
J. E. WHITE, 1956, 1958 (2)
LEO J. PETERS, 1932, 1949
G. C. SUMMERS, 1952

L. G. HOWELL, 1939, 1940, 1953, 1957, 1958
C. HEWITT DIX, 1939 (2), 1941, 1948, 1950, 1954, 1955 (2), 1958
HENRY FAUL and C. W. TITTLE, 1951 (2)
SIGMUND HAMMER, 1938, 1939, 1943, 1945, 1950
ENDERS A. ROBINSON, 1953, 1957
L. L. NETTLETON, 1934, 1939, 1942, 1944, 1947, 1954, 1957
F. J. McDONAL, F. A. ANGONA, and R. L. MILLS, 1958
D. S. HUGHES, 1942, 1951, 1952, 1953, 1956, 1957
T. A. ELKINS, 1938, 1944, 1951
R. D. WYCKOFF, 1941, 1948
F. A. VAN MELLE and K. R. WEATHERBURN, 1953
J. D. EISLER, 1947, 1951, 1954
ALFRED WOLF, 1936, 1937, 1940, 1944, 1945, 1946
M. B. WIDESS, 1940, 1943, 1946, 1952
EUGENE G. LEONARDON, 1936, 1948
ALEX FROSH, 1939
LOUIS CAGNIARD, 1953
ERIC BOISSONNAS, 1948
M. R. J. WYLLIE, 1955, 1956
VICTOR VACQUIER, CHARLES R. HOLMES, PAUL P. KINTZINGER and MICHEL LAVERGNE, 1957
A. R. GREGORY, 1956
W. G. HICKS and J. E. BERRY, 1957
J. P. WOODS, 1956
H. R. PRESCOTT, 1951
C. B. VOGEL, 1952
RALPH D. LYNN, 1950, 1958
E. J. STULKEN, 1945, 1951
D. SILVERMAN and J. F. EVANS, 1947, 1954
JAMES R. WAIT, 1951, 1953, 1954, 1955, 1956
HAROLD W. WASHBURN, 1937, 1940, 1941
L. H. BERRYMAN, P. L. GOUPILLAUD and K. H. WATERS, 1958 (2)
JACK OLIVER, 1954 (2)
FRITZ GASSMANN, 1951
LEON KNOPOFF, 1957, 1959 (2)
G. P. WADSWORTH, J. B. BRYAN and P. M. HURLEY, 1953
THOMAS C. POULTER, 1950
CLARK GOODMAN, 1951
J. M. KENDALL, 1941 (2)
C. Y. FU, 1946 (2), 1947, 1948
THEODOR KREY, 1952
C. H. GREEN, 1938
H. M. EVJEN, 1936, 1943

EDWIN B. NEITZEL, 1958
M. M. BACKUS, 1959
FRANKLYN K. LEVIN, 1955, 1958
C. F. HADLEY, 1954
MILTON B. DOBRIN, 1951, 1954 (2), 1956
CARL H. SAVIT, JOHN T. BRUSTAD, and JOSEPH SIDER, 1958
RICHARD N. JOLLY, 1953, 1956
A. W. MUSGRAVE, G. W. EHLERT, and D. M. NASH, JR., 1958

SIGNIFICANCE

A study of the types of papers receiving *classic* designation should be rewarding in serving to estimate the health of our science and the directions in which its development is presently continuing. High among the achievements are the efforts to formulate the laws and principles of our science. Two thirds of the *classics* are devoted toward that objective.

One of the most satisfying results to evolve from this study was in noting the unparalleled acclaim given to Dr. Norman Ricker while at the same time observing the high honors given to the papers of McDonal et al. and of Born, both of which reported results in disagreement with Ricker. This judgment does not represent two schools of thought, for without exception those nominating the McDonal et al. or the Born papers also nominated one or more of Ricker's *classics!* We believe this objectivity to be a most healthy attitude since this disagreement will eventually result in a more complete understanding of the laws governing attenuation and dispersion.

New methods and new techniques have naturally been of great interest. The continuous velocity loggers described both by Summers and Broding and by Vogel represent such an outstanding contribution that Hicks and Berry have received *classic* distinction in describing a special use of their tool. The logging papers by Howell and Frosh and by Faul and Tittle and again with Goodman are important *classics*. In the seismic field some of the works of Gardner, Ricker, Neitzel, Backus, and Savit et al., represent *classics* in methods and techniques. Mr. Carl Savit states: "The Poulter Method, while possibly somewhat disappointing in its direct application led to the useful multiple hole technique." Cagniard, Boissonnas and Leonardon, and Vacquier et al., made important contributions to electrical methods.

The growing improvement in interpretation techniques is shown by the papers of Van Melle and Weatherburn, Prescott, Peterson et al., Woods, Krey, Berryman et al., and by the model studies of Oliver et al., and Evans et al. In the gravity and magnetic field interpretation methods have been enriched by the contributions of Peters, Nettleton, Elkins, and Hammer.

Instrumentation has received some honors in our classic awards. Wyckoff and Washburn made important contributions as did also, Muffly, Loper and Pittman, and Palmer.

Analysis by Year and Volume

Displayed in Figure 1 by year and volume are the number of the papers published in GEOPHYSICS, the *Classic Papers*, and the total nominations. The first seven volumes (years) contained an imposing number of our *classics*. The years from 1942 through 1949 (Volumes VII through XIV) were lean years in the opinions of our judges. The years 1951 (Volume XVI) through 1953 (Volume XVIII) appear to be the years of highest quality with a moderate diminution in subsequent volumes. This same result can be seen for total nominations and is reflected to some degree in total papers. The sharp drop-off in nominations coincident with the vertical dashed line following 1953 in Figure 1 is partly due to the number of judges who did not consider these later volumes in their nominations. Even those judges who did consider the later volumes may have been more restrictive in their choices because of "newness." Mr. Paul Lyons, in his letter of transmittal of his nominations wrote: "Apparently a paper requires some aging to be appreciated. Also we cannot escape the obvious contribution of a 'first.' The earlier papers had the advantage in that regard." This able summation of the handicap pertaining to recent papers makes even more impressive the substantial number of *classics* selected from the latest volumes.

The Future of *GEOPHYSICS*

While the large number of *classics* selected from the first seven volumes (Figure 1) suggest a "Classic Age," both the total published papers and the number of *classic* selections disclose a "Renaissance" beginning about Volume XV, 1950. The intervening years (1943–1950), in keeping with this historical analogy, might be termed the "Dark Ages." In seeking an explanation for the "Dark Ages" it must be recognized that there is a considerable lag between cause and the effect on GEOPHYSICS. The war years and changing company policies on publication could be a partial explanation, but there may be another more basic reason. Exploration success had been so considerable that there was a tendency to "freeze the model." The methods that worked yesterday were considered adequate for tomorrow's problems. Interpreters had learned their trade by working under other interpreters and were graded on their ability to follow the pattern. During this period the statement was made that beyond a few minor changes there could be no further improvement in instrumentation. In the truest sense of the term the "Dark Ages" of geophysics had set in. It was assumed that all pioneering work had been done in what we have called the "Classic Age." Case Histories became the dominant feature of GEOPHYSICS. Since little in the way of major exploration improvement was considered probable many researchers turned their efforts toward collecting data and formulating some of the laws of geophysics. The fruits of these researches began to appear in 1950.

During these "Dark Ages" some companies usually either late starters in geo-

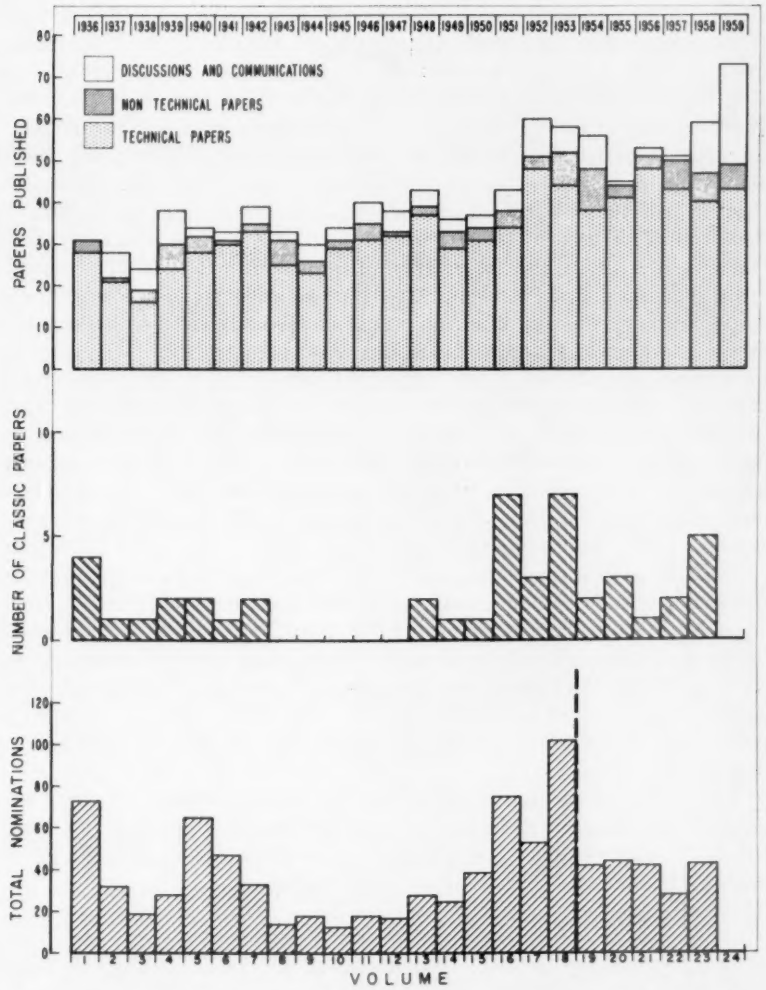
1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959
DISCUSSIONS AND COMMUNICATIONS
NON TECHNICAL PAPERS
TECHNICAL PAPERS
PAPERS PUBLISHED
NUMBER OF CLASSIC PAPERS
TOTAL NOMINATIONS
VOLUME

FIG. 1. Total papers published, number of *Classic Papers* and Total Nominations of the judges are shown by year and volume of GEOPHYSICS. Total nominations for the volumes after the dashed line (volume 18) are not comparable with prior years since fewer judges considered the later volumes. Only two issues of volume 24 were considered in classic nominations and the incomplete information on that volume including one classic paper is not shown.

physics or those realizing that geophysics as then practiced was failing to supply sufficient correct answers, inaugurated a crash program of research. The success of this program likewise became apparent about 1950. Thus the "Renaissance" period of 1950—was a time at which the contributions of those intent on formulizing the early data were overlapped by those seeking new approaches. Peters (1949) in magnetics and Poulter (1950) in seismic heralded the search for new approaches followed by Elkins (1951) in gravity. Summers and Broding (1952) and Vogel (1952) in a role of dual significance, contributed substantially to the seismic field and inaugurated a new logging method. Van Melle and Weatherburn (1953), Peterson et al., (1955), and Woods (1956) contributed materially to the appreciation of the significance of seismic records. In retrospect the work of Prescott (1951) looms as a pioneer step toward the new philosophy in geophysics. The significance of the early work of Rieber (1936), always of acknowledged importance, but never accepted as an integral part of the seismic method, now slowly began to be recognized as the implications of magnetic recording (Loper and Pittman, 1954) were gradually realized. The introduction to seismology of the approach to separation of low volume signal from higher amplitude noise (Wadsworth, Robinson, et al., 1953) not only offered possibilities of improving on principles enunciated by Eisler (Dyk and Eisler, 1951) and Frank and Doty (1953) but, together with the subsequent work of Robinson (1957) has had an influence far exceeding the immediate gains directly attributable to their suggested application. Some of the methods and philosophy of the currently developing continuous seismic wave method should be credited to the Wadsworth, Robinson et al. (1953), contributions. The paper of Backus (1959) derives in part from these works. At the same time and essentially independently of the Wadsworth-Robinson approach, techniques akin to the Rieber methods have received increased attention. Some of these approaches have been indicated in recent volumes of GEOPHYSICS but the final solution is not yet clear.

Our reading of the significance of the later *classics* reveals that today we are engaged in an accelerated investigation of data reduction methods, an intensive search for new techniques, and a continuing program of basic research. Far from being completed, our "Renaissance" is just beginning.

ACKNOWLEDGMENTS

We acknowledge our debt of gratitude to the judges: Curtis H. Johnson, Cecil H. Green, Frank Goldstone, Daniel Silverman, K. M. Lawrence, J. D. Eisler, Carl H. Savit, F. G. Boucher, John M. Crawford, F. F. Campbell, Charles H. Fay, James F. Johnson, Theodore R. Madden, J. E. White, John Owen, J. P. Woods, Andrew Gilmour, Paul L. Lyons, Edgar J. Stulken, W. T. Born, Irwin Roman, W. P. Hasbrouck, Paul A. Rogers, G. E. Archie, O. F. Ritzmann, Norman H. Ricker, T. A. Elkins, Franklyn Levin, T. C. Richards, Peter Dehlinger, and Kenneth L. Cook.

Their contribution in time and thought was much greater than that implied, rather glibly, in our letter of solicitation.

References

Complete references for all papers mentioned in this article together with others qualifying as Distinguished Papers are presented in alphabetical order by year and volume in EDITORS OF GEOPHYSICS, Pages 25–55.

PRECURSORS OF *GEOPHYSICS*

HISTORY

The first geophysical papers published under the auspices of the Society of Petroleum Geophysicists appeared in the BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, Volume XV, Numbers 11 and 12. These were designated TRANSACTIONS OF THE SOCIETY OF PETROLEUM GEOPHYSICISTS, Volume I. Volume II of the TRANSACTIONS appeared in PHYSICS in March 1932. Volumes III, IV, and V were published in the AAPG BULLETIN in December 1932, January 1934 and January 1935.

The first journal published by the Society appeared under the title THE JOURNAL OF THE SOCIETY OF PETROLEUM GEOPHYSICISTS, Volume VI, Number 1, July 1935. Volume I, Number 1 of GEOPHYSICS was published in January 1936. The present issue of GEOPHYSICS, Volume XXV, Number 1, therefore, also marks the beginning of the second quarter century of SEG publications.

Mr. Paul Weaver, the Society's first Editor states in a private communication: "The beginning of application of geophysics to prospecting saw two new magazines in German: Zeitschrift für angewandte Geophysik in 1924 and Zeitschrift für Geophysik in 1925. In this country the AIME published a collection of papers: GEOPHYSICAL PROSPECTING, 1929. It should be realized that very few of the clients of the geophysicists were willing to see case histories published of work done for them, and it was the AIME volume that 'broke the ice.' The existence of these publications was very persuasive that our Society should try its own publication. I think we owe a debt to the American Physical Society whose support enabled us to obtain AAPG support."

The chief function of the Editors of these early volumes was that of obtaining geophysical papers. It is clear from Paul Weaver's comments that securing the release of manuscripts required major effort.

The papers published by AAPG were edited by Dr. B. B. Weatherby who served as AAPG Associate Editor for Geophysics from 1931 through 1935.

The Editors of these early geophysical papers, their terms of office and SOME OUTSTANDING PAPERS as nominated by the judges of CLASSICS OF GEOPHYSICS (pages 2–15) are presented in the following pages.

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PAUL WEAVER

Editor 1931–1932
Transactions of the Society of Petroleum Geophysicists
Volume 1

L. W. BLAU

Editor 1932–1934
Transactions of the Society of Petroleum Geophysicists
Volumes 2 and 3

B. B. WEATHERBY

Editor 1934–1935
Transactions of the Society of Petroleum Geophysicists
Volumes 4 and 5

F. M. KANNENSTINE

Editor 1935–1937
The Journal of the Society of Petroleum Geophysicists
Volume 6

SOME OUTSTANDING PAPERS

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ROSAIRE, E. E. and LESTER O. C., JR., Seismological Discovery and Partial Detail of Vermilion Bay Salt Dome, Louisiana

SLOTNICK, M. M., Curvature of Equipotential Surfaces

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WEATHERBY, B. B. and FAUST, L. Y., Influence of Geological Factors on Longitudinal Seismic Velocities

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THE FOUNDING OF *GEOPHYSICS*

B. B. WEATHERBY†

The first issue of GEOPHYSICS contained the Editor's Report. That report made the following brief mention of the inauguration of this journal: "The Executive Committee has ordered the title of our publication to be changed to 'GEOPHYSICS' of which this is Vol. 1, No. 1." The first volume published by the Society had appeared the previous year (1935) under the title THE JOURNAL OF THE SOCIETY OF PETROLEUM GEOPHYSICISTS. During 1935 there was agitation for a change of name of the Society. This resulted in a petition being presented to the Executive Committee for an amendment to the Constitution to change the name to AMERICAN GEOPHYSICAL SOCIETY. That committee realized that a broader name for the Society was desirable, but that AMERICAN GEOPHYSICAL SOCIETY, while enlarging the scope of activities, restricted their boundaries. The present more embracing title of our Society was not adopted until 1937. Fearing that the title of the original volume might brand the infant journal as illegitimate, the Executive Committee decided on a title for the publication not containing the name of the Society. This had the added advantage of distinguishing the journal from a host of other technical magazines, in the titles of which, in many instances, the full name of the publishing society has been incorporated making them of burdensome length. The decision to name it GEOPHYSICS was made only after careful consideration.

EDITOR'S NOTE: A reproduction of the front and back covers of GEOPHYSICS, Volume I, Number 1, appear on the following two pages.

† Senior Vice President, Amerada Petroleum Corporation, President of the Society of Petroleum Geophysicists at the founding of GEOPHYSICS.

Volume 1 Number 1

GEOPHYSICS

A Journal of General and Applied Geophysics

JANUARY, 1936

Published by the

SOCIETY OF PETROLEUM GEOPHYSICISTS

Volume I JANUARY, 1936 Number 1

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Society of Exploration Geophysicists

The First Editor of Geophysics

1935–1937

F. M. KANNENSTINE

EDITOR OF { Volume I, Numbers 1, 2, 3
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Associate Editors

E. E. ROSAIRE

M. E. STILES

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* *Classic.*

The Second Editor of Geophysics

1937–1939

M. M. SLOTNICK

EDITOR OF { Volume II, Numbers 2, 3, 4
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Associate Editors

E. E. Rosaire

H. B. Peacock

C. E. Houston

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R. D. WYCKOFF

EDITOR OF { Volume IV, Numbers 2, 3, 4
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Non-Technical Papers	11
Communications	8
Reviews	18

Edited more issues than any other Editor.
Inaugurated Patents Section and Contributors' Section.

* *Classic.*

The Fourth Editor of Geophysics

1942–1945

JOSEPH A. SHARPE

EDITOR OF { Volume VII, Numbers 3, 4
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* *Classic.*

The Fifth Editor of Geophysics

1945–1947

L. L. NETTLETON

EDITOR OF { Volume X, Numbers 3, 4
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Inaugurated First Reviews Committee.

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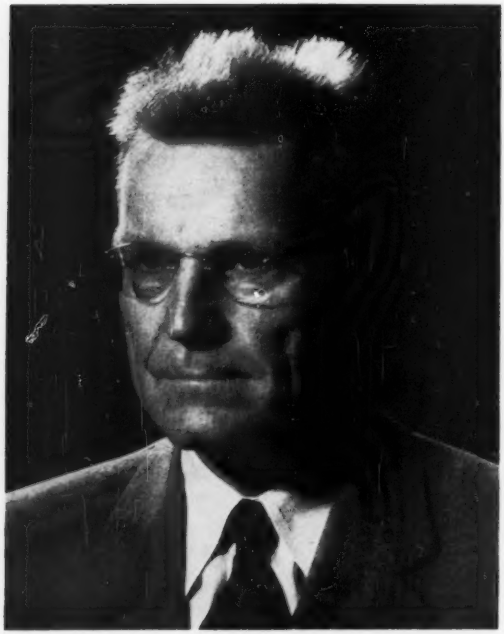
The Sixth Editor of Geophysics

1947–1949



M. K. HUBBERT

EDITOR OF { Volume XII, Numbers 3, 4
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The Seventh Editor of Geophysics

1949–1951

RICHARD A. GEYER

EDITOR OF { Volume XIV, Numbers 2, 3, 4
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1951–1953

PAUL L. LYONS

EDITOR OF { Volume XVI, Numbers 3, 4
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NELSON C. STEENLAND

Chairman, Publications Committee

W. T. BORN

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Inaugurated Publications Committee

The Ninth Editor of Geophysics

1953–1955

MILTON B. DOBRIN

EDITOR OF { Volume XVIII, Numbers 2, 3, 4
Volume XIX, Numbers 1, 2, 3, 4
Volume XX, Numbers 1, 2, 3, 4

Associate Editors

NORMAN RICKER
Seismic Theory and Fundamentals

L. Y. FAUST
Seismic Techniques and Operations

THOMAS A. ELKINS
Gravity Prospecting

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* *Classic.*

The Twelfth Editor of Geophysics

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NELSON C. STEENLAND

WHO WILL SERVE AS EDITOR FOR { Volume XXV, Numbers 2, 3, 4, 5, 6
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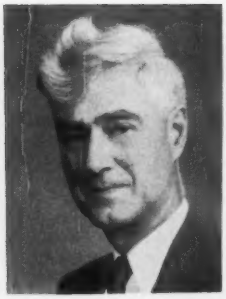

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The Patent Section of GEOPHYSICS was initiated with the October, 1939 issue during the administration of SEG President E. A. Eckhardt. The patent abstracts were prepared by Mr. Gary Muffly from October 1939 through July, 1941, and by Mr. B. Perkins, Jr. for October, 1941 and January, 1942. Beginning with April, 1942 the Patent Section has been the responsibility of Mr. O. F. Ritzmann who has prepared the abstracts for every issue of GEOPHYSICS since then.

In 1954 Mr. Ritzmann was elected a Life Member of SEG in recognition of his many years of service to Exploration Geophysics in providing material for the Patent Section.

Special Editor for Early Geophysical Papers

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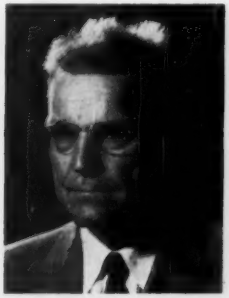
Dr. Nettleton, during his term as Editor acted as his own Special Editor in assembling the papers of the six volumes preceding GEOPHYSICS (see pages 16–18) plus three special papers into a volume entitled *Early Geophysical Papers.*

PUBLISHED 1947

Special Editors for Cumulative Index

R. D. Wyckoff
1931–1940



M. King Hubbert
1931–1947

Kenneth L. Cook
1931–1953

The first Cumulative Index was prepared by R. D. Wyckoff while Editor and appeared in July, 1940 as Volume V, Number 3, Part 2. A special volume was prepared by M. King Hubbert while Editor and published in 1948. The most recent Cumulative Index to date was edited by Kenneth L. Cook during the term of Milton B. Dobrin, Editor, Society of Exploration Geophysicists. This latest index was published in 1955. The next Cumulative Index should appear in 1961 or 1962.

Special Editor for Geophysical Case Histories Volume I

L. L. NETTLETON

A collection of sixty papers was prepared by Dr. L. L. Nettleton, Special Editor, during the term of office of SEG Editor, Dr. M. King Hubbert. Of the sixty papers, one third were new and prepared especially for this volume. The others had been published previously, some in other journals as they include work prior to Volume I Number 1 of GEOPHYSICS.

The preparation and publication of geophysical case histories was a project enthusiastically promoted by Henry C. Cortes during and following his term as President of the Society.

PUBLISHED 1948

Special Editors for Index of Wells Shot for Velocity

B. G. SWAN

As a contribution toward a wider distribution of well velocity information, Mr. B. G. Swan prepared the first Index of Wells Shot for Velocity, which was published in GEOPHYSICS Volume IX (October 1944). Three supplements were published by Swan in Volumes XI (October 1946), XIV (January 1949) and XVI (January 1951). All of this material was reindexed by the Society's editorial Staff, reproduced by photo-offset printing, and in 1953 published as a booklet entitled *Index of Wells Shot for Velocity*.

V. U. GAITHER

Mr. Gaither has continued Swan's work publishing Supplements Four through Eight in Volumes XXI (January 1956), XXII (January 1957), XXII (December 1957), XXIII (December 1958), and XXIV (December 1959). These have been made available by the Society in reprint form.

Special Editor for Geophysical Case Histories Volume II

PAUL L. LYONS

The editing of this collection of fifty-three papers was begun by Paul L. Lyons under SEG Editor Milton B. Dobrin and completed under SEG Editor Norman Ricker. Type of trap or objective is the basis for grouping in this second volume which is world-wide in its scope.

Mr. D. P. Carlton served as Chairman of the Committee on Geophysical Case Histories throughout the assembling of papers for this volume.

PUBLISHED 1956

Special Editor for Lessons in Seismic Computing

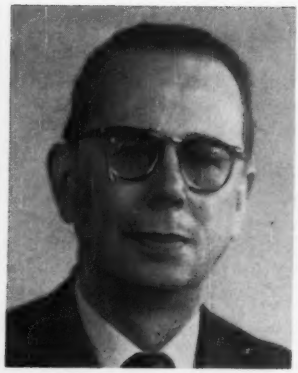
RICHARD A. GEYER

Dr. Geyer served as Special Editor for *Lessons in Seismic Computing* under SEG Editor Lawrence Y. Faust. This volume, a Memorial to the author, Morris Miller Slotnick, was published by permission of Humble Oil and Refining Company and of Mrs. M. M. Slotnick.

PUBLISHED 1959

Best Paper Award Winners

1947



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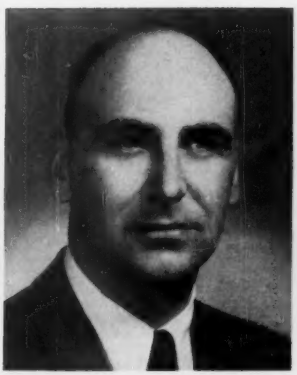

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Among Colin Campbell's many duties has been the responsibility for advertising in GEOPHYSICS, a duty of the Business Managers beginning with the Editorship of M. M. Slotnick. Since 1959 the solicitation and processing of advertising has been delegated to Assistant Business Manager W. L. Latting.

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For services rendered far in excess of normal commercial responsibility, the Editors of GEOPHYSICS, the Editors of Special SEG Publications, the SEG Executive Committees, and the SEG Business Manager join in acknowledging their debt of gratitude to Clark A. Wiese. The George Banta Company, Inc. has published every volume of GEOPHYSICS. To the Editors, Clark Wiese symbolizes Banta. A veteran of over fifteen years with Banta at the time of the founding of GEOPHYSICS, Clark Wiese has been responsible for the publication of every issue. When crises arise, and they have been numerous, Wiese's replies to the Editors' queries are invariably, "we will manage somehow," then meets the crisis both well and expeditiously.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 77-91

A REVIEW OF GEOPHYSICAL INSTRUMENTATION*

W. T. BORN†

ABSTRACT

This paper is a historical review of the development of instrumentation used in all phases of geophysical prospecting, including well logging. Particular reference is made to pertinent papers published in GEOPHYSICS and its predecessor publications.

A good historical review of the progress in instrumentation cannot be written solely from a perusal of papers in GEOPHYSICS. This incomplete account is based upon material which that journal has published, somewhat amplified by the writer's recollection of early developments within a company which was one of the pioneers in the application of geophysical methods to exploration for oil.

At the present time highly sophisticated instrumentation is commercially available for the practice of every type of geophysical exploration. The design and construction of instruments is now the function of specialists in electronic and mechanical engineering, and is of interest to comparatively few readers of GEOPHYSICS. It is therefore not strange that very few papers concerning instrumentation are currently published. Information concerning modern instrumentation is readily available from manufacturers, most of whom are represented in the advertising pages of GEOPHYSICS. The progress in instrumentation during the past 15 years can be followed quite well by perusing the advertisements.

The early issues of GEOPHYSICS also contain but few papers concerned primarily with instrumentation, but for quite a different reason. The subject was then of tremendous importance and of great interest to all readers because instrumentation for the practice of the seismic methods was not commercially available. Great competitive advantage accrued to the company which first developed new or improved instrumentation. Details of instrument design were therefore highly protected trade secrets to be divulged only when necessary in making patent applications.

Since October of 1939, GEOPHYSICS has carried a feature which is of tremendous value to the technically minded reader. This is an index of patents pertaining to the geophysical field, each one classified and abstracted. The feature is a contribution of O. J. Ritzmann and his associates in the patent department of the Gulf Oil Corporation. Anyone seriously interested in instrumentation either past or present will profit greatly by careful examination of these compilations. Suggested reading in this connection is a paper by Ritzmann (1957).

GEOPHYSICS has published a number of excellent historical papers which

* Manuscript received by the Editor October 27, 1959.

† Geophysical Research Corporation, Tulsa, Oklahoma.

describe the introduction of geophysical methods to the oil industry. Most of these papers discuss both instrumentation and techniques, in a general way.

DeGolyer (1935) tells of the introduction of the Eötvös torsion balance about 1922, of the seismic refraction method in 1924, and of the seismic reflection method in 1926. Weatherby (1940) tells the story of seismic work in more detail, and discusses the important instrument improvements made up to 1940. Schriever (1952) recounts the experimental work of Karcher and others attempting to develop the reflection seismic method in the early 1920's. Heiland (1932) describes some of the early attempts to employ electrical prospecting methods. His paper includes a good bibliography of early papers on the subject. Rust (1938) gives a brief review of the same subject and also gives a good list of references. An excellent historical account of the development of instruments and techniques used in gravitational methods is given by Eckhardt (1940) who pioneered in that field.

All of the papers mentioned above have become easily available through the republication of back numbers of GEOPHYSICS. Younger members of SEG will find them fascinating reading.

MAGNETIC METHODS

Geophysical methods were used (and misused) in the search for ore bodies many years before they were applied in the petroleum industry. Undoubtedly the first geophysical instrument is the compass, which indicates the direction of the horizontal component of the earth's magnetic field. In fact, by suitable manipulation of an auxiliary magnet placed near a compass needle, a crude measurement of the field intensity can be made. Such a device is described by Wilson (1931). The dip needle was also used long, long ago in exploration for magnetic ore bodies. It has been used as a crude magnetometer for measurement of the vertical component of the earth's field (Swanson, 1936). About 1915, Schmidt developed the horizontal and vertical magnetic field balances still known by his name. Within a few years these became commercially available and the Schmidt Vertical Magnetometer rapidly found an important place in both the mining and petroleum industries. Its modern versions are still the instruments most used in making magnetic surveys at ground level.

In the early 1940's there occurred a revolutionary development, that of the airborne magnetometer based upon the invention of a flux-gate magnetometer by V. Vacquier of the Gulf Research and Development Company. The early development of this instrument is described by Muffly (1946) and a complete description of the instrument is given in a very fine paper by Wyckoff (1948). It is not generally known that the first application of the airborne magnetometer was the detection of submarines during World War II. Of the many unsung contributions made to the war effort by exploration geophysicists, this one is outstanding. The following quotation from Wyckoff is of interest in this connection:

" . . . By 1941, however, he, (Vacquier), had succeeded in developing an ele-

ment of the flux-gate type having a very high sensitivity and a physical form amenable to airborne application. At about this time, the war menace had become increasingly alarming, and effort was immediately concentrated on the possible use of the new element as an airborne submarine detector and as the influence member in submarine and land mines.

"After preliminary work demonstrating that the sensitivity attained by the new element was sufficient to detect a submerged submarine at a reasonable distance, support of the project by N.D.R.C. was obtained and the problem of orientation stabilization was attacked by the then most expedient means in order to establish the practicability of airborne operation with the least possible delay. The first relatively crude orienting system successfully demonstrated the practicability of the scheme. In fact, the experiment was rather quickly followed by the successful detection and disposal of an enemy submarine in an operational test flight of this early experimental model in December, 1942."

Various versions of the airborne magnetometer are today extensively used by both the petroleum and mining industries, primarily for reconnaissance work in new areas. An essential part of the instrumentation needed for such surveys are radio location devices used to keep the survey plane on known courses. Details of these techniques are not to be found in GEOPHYSICS.

ELECTRICAL METHODS

Electrical methods were introduced in the mining industry prior to 1920 and were used to some extent by the petroleum industry after 1925. The most important electrical methods are essentially techniques for measuring earth resistivity by producing a flow of current in the earth and mapping the resulting potential fields. The current may be introduced into the earth conductively by electrodes, or by induction from a coil of wire carrying a current. The excitation may be by direct current, alternating current, or a transient pulse of current. The instrumentation required is relatively simple and a great variety of devices have been used.

The interpretation of the data obtained from electrical surveys is extremely difficult and the theoretical work upon which interpretation should be based is tedious, and involved. Although GEOPHYSICS has carried many papers on the subject, none of them is concerned primarily with instrumentation. There are many theoretical papers and many accounts of field experimentation, most of which mention the type of instrumentation used. Typical papers describing direct-current resistivity work are those of Blondeau (1939) and England (1941). West (1938) and Klipsch (1939) describe early work using transient excitation.

Other techniques are essentially methods of measuring natural potentials produced by physical-chemical reactions between adjacent but dissimilar materials within the earth.[1] These techniques can be used to locate some types of ore bodies.

[1] Editor's Note: See Sato and Mooney, The Electrochemical Mechanism of Sulfide Self-Potentials, p. 226, this issue.

They have proved to be of great value in well logging to obtain the familiar "Self-Potential" log. The instrumentation is again very simple. All that is needed is a pair of electrodes and a recording potentiometer.

There are a number of other electrical exploration methods of minor importance. One technique is that of mapping the natural potential field produced by telluric currents, which flow in vast sheets involving large areas of the earth. The apparatus required is again only a number of electrodes and a recording potentiometer. (Boissonas and Leonardon, 1948). Efforts have been made to utilize polarization phenomena by passing current through the earth, then disconnecting the current source, and observing the decay of the resulting potentials after the exciting current ceases to flow. This technique is discussed in papers by Bliel (1953) and by Vacquier, et al. (1957).

Electrical surveys, conducted on the surface, are of little importance in exploration for petroleum because they can delineate only relatively shallow features. On the other hand, the same methods applied to well logging are of tremendous economic importance. Introduced in 1929 by Conrad and Marcel Schlumberger, electrical well logs have become an indispensable tool of petroleum engineers and of geologists. Papers concerning these methods have been published in journals other than GEOPHYSICS, many of them in publications of the A.I.M.E.

Although electrical methods are today extensively used in the mining industry, descriptions of modern techniques have not yet been published in GEOPHYSICS. The most interesting recent development is that of airborne equipment for conducting electromagnetic surveys.

GRAVITY METHODS

At the time that the need arose for geophysical prospecting methods an instrument for gravitational surveying was already available in the Eötvös torsion balance. This is an instrument which measures the horizontal gradients and curvature values of the gravitational field. It was invented by Baron Ronald von Eötvös, a Hungarian physicist interested in geodetic problems. The balance he built about 1902 was practically the same design as those sold commercially some twenty years later.

The torsion balance was a very important geophysical instrument for almost twenty years. Torsion balance surveys were first made in the U.S.A. in 1922, and the peak of activity was reached in 1935. Since the instrument was well-known at the time GEOPHYSICS began publication, writers of papers describing torsion-balance surveys did not include a description of the instrument.

Although the torsion balance was a very useful and valuable instrument, it required highly skilled operators, was cumbersome to transport and set up in the field, and many hours were required to make a single observation. Since it responded to the horizontal gradient of gravity, which is greatly affected by local irregularities in terrain, the reduction of the observed data was quite a chore.

During the decade 1925 to 1935, the efforts of many physicists were directed toward the design of instruments which would respond directly to the acceleration of gravity rather than to its horizontal gradient, in order to minimize terrain corrections. The pendulum is such an instrument, but the finest pendulum equipment available in 1925 did not possess the required accuracy needed for geophysical exploration. For this use an accuracy of one part in ten million or better is required. Eckhardt and Wyckoff, then with the Marland Oil Company, later with Gulf, succeeded in building penduli made of quartz and developing an operating technique which gave the desired results, (Gay, 1940). Pendulum equipment was used by the Gulf organization for a few years but never came in general use. It was soon supplanted by the gravimeter.

The gravimeter, or gravity meter, is in principle a very simple instrument, but the design and construction of a useable instrument is a formidable task. In its elementary form it is simply a very small mass suspended by a very weak spring. At a given location the extension of the spring is determined by the mass and the acceleration of gravity at that point. The change in gravity between two points is thus measured by the difference in the extension of the spring observed at those points—or rather, it would be if the instrument were unaffected by temperature, if the spring were perfectly elastic, etc. Instead of observing the extension of the spring directly, a calibrated auxiliary spring may be employed to return the mass always to a definite position, thus making the instrument a null reading device. This feature is found in many gravity meters commonly used although they may differ greatly in other respects.

The simple instrument just described is a non-astatic type. The first description of such an instrument, published in GEOPHYSICS, is that of Hartley (1932). An unusual version of a non-astatic type meter is the Gulf Gravimeter described by Wyckoff (1941). The mass in this instrument is suspended from a ribbon in helical form. Changes in the weight of the mass cause it to rotate. The rotation is observed by means of a mirror, attached to the mass, and a multiple reflection arrangement to obtain magnification. The Gulf Gravimeter was in extensive use from 1935 on. A few years later it was adapted for underwater use by attaching means for photographic recording and mounting the instrument on gimbals within a watertight case. Leveling is done by servo-motors remotely controlled (Pepper, 1941).

Many gravity meters employ the principle of astatization by incorporating means for actually increasing the displacement of the suspended mass by introducing a negative restoring force, that is, one which opposes the restoring force of the suspended spring when the mass moves from its position of equilibrium. The possible ways of applying this principle are limited only by the ingenuity of the designer. One of the earliest successful astatic gravimeters was that designed by Truman of the Humble Oil and Refining Company and used in the field as early as 1930. It is described in a paper by Bryan (1937).

By 1940 a number of other designs of gravimeters were available. Among them

were those of Mott-Smith, Brown, Sweet, LaCoste-Romberg, and Kannenstine in this country; Graf, Ising, von Thyssen, and Lejay in Europe. Unfortunately, none of these men has published descriptions of his design in GEOPHYSICS. Undoubtedly many trade secrets were involved, so publicity was not sought. Mott-Smith (1937) published an interesting paper on gravitational surveying. He shows a picture of the encased instrument, but of its design he makes only the intriguing statement that, "In principle our Meter is a mass on a spring, . . . except that we have no helical spring and practically no mass." The statement was correct. The Mott-Smith (1938) instrument is an astatic type employing a horizontal torsion fibre carrying a very small mass. The entire assembly is made of fused quartz and weighs only a few ounces. This design was important because it showed that a gravimeter element could be made very small. This design trend culminated in the present-day Worden gravimeter, which weighs only five pounds complete, and requires no external power source for temperature control. In contrast, the early models of the Gulf and Humble meters weighed approximately 100 pounds.

The story of the gravimeter well illustrates the truth of the old saw that "the impossible takes a little longer." It was in 1833 that Sir John Herschel suggested that gravity might be measured by a mass suspended on a spring. In the next hundred years many ingenious physicists and technicians devoted themselves to implementation of this suggestion, each profiting by the experience of his predecessors. Only a few of these have been mentioned above. The story is not yet finished. LaCoste in this country, and Graf in Europe, have designed gravimeters and stabilizing systems which may be used aboard surface vessels, and an airborne version of the instrument is under development.[2]

SEISMIC METHODS

The torsion balance was available for gravitational surveying long before the need for such work arose. A similar situation did not exist in the case of seismic prospecting. The practice of the methods now employed had to await the development of suitable instrumentation. This was hardly possible until the advent of the vacuum tube amplifier. The development of basic instrumentation took place between 1925 and 1930, before GEOPHYSICS began publication. Some significant improvements were made during the next ten years but little new has been added since, except the introduction of instrumentation for obtaining reproducible seismic records. This important development was made by the late Frank Rieber about 1936, but was not widely exploited until the advent of magnetic recording techniques in the 1950's.

Some limited success attended the earliest application of refraction shooting by Mintrop using a dynamite explosion for a source of seismic waves and a mechanical seismograph for recording. The sensitivity of the recorder was quite inadequate. The introduction of an electrical detector coupled with a vacuum

[2] Editor's Note: See Nettleton, LaCoste, and Harrison, Tests of an Airborne Gravity Meter, p. 181, this issue.

tube amplifier really marked the beginning of present-day instrumentation. The first successful use of such equipment in the early months of 1926 is generally credited to the Geophysical Research Corporation. The detector used in that early work was a variable reluctance type using parts from a Baldwin headphone. A mass suspended from a diaphragm spring was attached to the armature pivoted between the poles of a permanent magnet. The amplifier was a simple resistance-coupled type, using one of the few vacuum tubes then available, the notorious W.E. 215-A. The oscillograph used the film transport mechanism of a hand cranked 35 millimeter movie camera. The two galvanometers in the oscillograph were of the rotating coil type with a natural frequency about 50 cps. Timing lines were obtained by shining a light onto the film through slits attached directly to the prongs of a massive 50 cps contact driven tuning fork. Timebreaks were transmitted by interrupting the transmission of a simple C.W. transmitter. The signals were picked up by a receiver employing two stages of the then new Hazeltine "Neutrodyne" circuit, (the controls of which were made conveniently accessible to induce regeneration when sensitivity was needed). Surveying was done by recording the sound waves, generated at the shot point, by a so-called blast phone. This was similar to those developed during World War I for sound ranging on enemy guns. It consisted of an air chamber closed by a thin diaphragm to which was attached a carbon button, coupled through a transformer to a galvanometer. The only access to the diaphragm was through a very small orifice which acted as a low-pass filter for impinging sound. The instrument was quite insensitive to ordinary airborne noise but responded well to the low frequency component of the blast from a shot. Crude as this apparatus was, it proved superior to the mechanical seismograph. The weakest link was the geophone which was fragile and lacked sufficient sensitivity. It was soon supplanted by a dynamic type geophone weighing some 12 pounds, oil damped, about 10 cps natural frequency.

The first reflection shooting, done by the Geophysical Research Corporation in late 1926, employed essentially the same equipment. A third galvanometer was soon added and the natural frequency of the galvanometers was increased to 300 cycles because it was realized that high frequencies should be recorded to obtain high resolving power. Only a little field experience was required to indicate that the signal to noise level had to be improved by reducing the pass-band in order to eliminate low frequency ground roll and high frequency noise. Amplifiers for reflection shooting were then built with transformer coupling between stages, designed to cut off at about 30 cps. The galvanometer natural frequency was reduced to 90 cps, and the geophone natural frequency raised to 30 cps. New oscillographs were soon built to permit the recording of six channels at one time. As reflection shooting extended to other regions, it was found desirable to add additional filtering. This was first done by providing removable filters to be inserted between the geophone and the amplifier input. After some years, sufficient experience with filtering was gained to warrant building new amplifiers having self-

contained filters with switch selection for the cut-off. As instrumentation was made more reliable, the number of channels recorded simultaneously was gradually increased. By 1940 most crews used 10 or 12, and shortly thereafter the number was further increased to the present-day practice of using 20 to 24.

Many other companies were actively developing instruments in the years following 1925. It is probable that their efforts followed more or less parallel paths. It is known that much effort was devoted to design of geophones, first in an effort to obtain rugged instruments of high sensitivity, later to reduce their size. The large size and weight of early models, while partly due to poor design, was largely unavoidable. Geophone output had to be high because the vacuum tubes available in the early days had inherent noise levels many times higher than those now used. The usable amplifier gain was thereby limited. Magnet materials available had low coercive force and low energy content, so large magnets were needed to obtain the flux required in the air gap for high output.

Some companies developed the balanced armature reluctance type geophone, others the moving coil dynamic type. By 1935, both were in common use, most of them oil damped, although one company was using an air damped moving coil device. By 1937 electrically damped geophones were in use, their development having been made practical by the availability of new magnetic materials. The increasing use of many geophones per channel caused a demand for smaller and lighter geophones resulting in the miniatures of today. Again, this demand was met by the use of modern magnetic materials, and by reducing the output of the geophones. The low noise level of modern vacuum tubes permit the use of very high gain amplifiers, hence low sensitivity geophones are practical.

None of the papers published in GEOPHYSICS give details of geophone design and construction, but their behavior has been thoroughly analyzed in a number of excellent papers. Among these are those of Scherbatskoy and Neufeld (1937), Silverman (1939), Sparks and Hawley (1939), and Prescott (1941).

In retrospect it seems peculiar that many early geophone designers employed a suspended mass much greater than was really necessary, thus accentuating the damping problem. It is possible that they were influenced by the design of earthquake seismographs which employed large masses because they were of extremely long period and were required to supply appreciable power to a recorder. Many years later Wolf (1942) analyzed the problem and showed that, while there is a limiting value for the mass, it can be very small in the case of geophones used in seismic prospecting.

Some companies designed and employed string galvanometers in oscillographs for a number of years but their disadvantages soon became apparent and they dropped out of use.

About 1932, an instrumental improvement of great economic value came into use. This was a method of automatically controlling the gain of an amplifier so that early and late reflections were recorded with approximately the same amplitude. This was first done by automatically increasing the amplifier gain as a

function of time after the time-break. This was accomplished simply by a capacitor-resistance network of long time constant controlling the grid bias of one or more amplifier tubes. A few years later, circuits were developed which employed feedback from the amplifier output through an integrating network to control an attenuator within the amplifier, thus adjusting the gain of the amplifier by the amplitude of the incoming signal, averaged over a short period of the order of 0.1 second. This is the so-called A.A.C.—Automatic Amplitude Control. Most modern amplifiers incorporate both systems which may be used simultaneously.

Nearly a quarter of a century ago, Rieber (1936) published a paper describing a new method of recording and processing seismic reflection records This paper was followed by two (Rieber, 1937), (Johnson, 1938), describing application of the method. Rieber built, and used, an oscillograph which produced a variable density record on film. He also built playback equipment in which each trace was scanned by a beam of light passing through a narrow slit, thence through the film to a photo-electric cell, the output of which could be re-recorded in the form of a conventional record or added together to give a composite record. Moreover, the scanning slits were moveable so that the record could be repeatedly scanned, each time with the slits adjusted for a different stepout across the record. The outputs of all the photocells, when added together, should be a maximum when the stepout of the slits matches the stepout of a reflection. Mr. Rieber strongly advocated the use of such analysis to determine the dip of layers produca reflection. He believed that many so-called N.R. records actually were records which had reflections coming from several directions, but arriving at the same time, and that these could be sorted out by his analyzer.

Rieber's paper created great interest and aroused much discussion, some of it pointing out rather acrimoniously the defects of the suggested method. Strangely enough, at that time, neither Rieber himself nor those who discussed his work, realized the advantages of the variable density recording in data presentation. In fact, Rieber said in his early paper: "These records are usually without much visual significance, and are intended solely to make possible the second step, that of directional analysis." To this statement none of his critics took exception! Years later Palmer (1957) published an award winning paper describing elaborate and sophisticated equipment for making and processing variable density records. Mr. Palmer pays tribute to Frank Rieber as a pioneer and clearly indicates that the modern variable density record section stems from his early work.

During and after World War II, there was rapid progress in the art of recording on magnetic tape. The value of this method of making reproducible seismic records soon became apparent. By 1954 recording and playback equipment was commercially available. Before that time several companies had built equipment for their own use. Loper and Pitmann (1954) describe equipment used experimentally by the Magnolia Petroleum Company.

It is not possible to describe all the varied equipment now available. It is

sufficient to say that a considerable number of manufacturers offer good equipment to produce magnetic records and to re-record them corrected for weathering and stepout as a function of depth. Playback equipment is available to produce cross sections with any desired manner of presentation.

The advent of magnetic recording made possible a technique introduced by Burton McCollum some years ago. Dynamite is eliminated as a source of seismic waves and is replaced by dropping a heavy weight. Each drop produces a record on which reflections are usually not perceptible. By recording a large number of such drops separately and then adding them together, a usable record is obtained in some regions. Usually the drops are distributed over a considerable area and the individual records are corrected for stepout before being added together. Neitzel (1958) describes in some detail the instrumentation of the method and gives the results of experimental work done by the Atlantic Refining Company. Domenico (1958) tells of extensive experimental work performed by the Pan American Petroleum Corporation, and gives a brief description of the apparatus used.

Magnetic recording apparatus is also being used in research on a number of esoteric methods of record analysis. There is some hope that cross-correlation techniques useful in other fields of endeavor may be applicable to seismic data. Jones (1955) describes a magnetic delay line filter which may be used to cross-correlate a known signal with a record having the signal in the presence of noise. It has other applications also. Undoubtedly much similar work is as yet unpublished.

RADIOACTIVITY METHODS

Radioactivity well logging methods are of great importance to the oil industry, but surface surveys have not been of value in prospecting for petroleum.

In the early days of geophysical prospecting some abortive efforts were made to employ surface radioactivity prospecting for petroleum. These were confined to the measurement of the ionizing power of gases extracted from the soil using the only instruments then available for the purpose—the gold leaf, or the quartz fibre, electroscope. Such apparatus is described in a paper by Howell (1933). In later years much effort was devoted in attempts to find some empirical relationship between surface radioactivity and the presence of oil fields at depth. These efforts were intensified after World War II when improved Geiger counters and scintillation counters became available for the detection of gamma rays. None of this work has been published in GEOPHYSICS. Thus far these efforts have been unsuccessful.

On the contrary, radioactivity surveys have become a very important technique in mining geophysics, primarily because of the intensive search made for uranium-bearing ores during and after World War II. Geiger counters and scintillation counters have been incorporated in instrumentation for mak-

ing airborne surveys from low flying planes or helicopters. Well logging methods, developed by the petroleum industry, are also extensively used in prospecting for uranium. (Broding and Rummerfield, 1955).

WELL LOGGING

Most of the well logging techniques now in use were introduced by physicists and engineers whose primary interest was geophysical exploration. (The Schlumberger brothers' early efforts were devoted to electrical surveys on the surface.)

Prior to the advent of geophysical methods in this country, the oil industry employed almost no physicists or men of similar training. To develop geophysical instrumentation and techniques, many companies established geophysical laboratories staffed for the most part with physicists and electrical engineers who had no previous knowledge of the oil business. As these men became acquainted with the problems facing those engaged in petroleum activity, they were able to make many contributions to other phases of the industry.

Resistivity well logging, introduced in 1929, proved to be a great boon to geologists for correlation work and an invaluable aid to production men. About 1935, several companies began to seek other methods of well logging which would permit logging a well after it was cased. It was known that traces of radioactive elements are found in many earth materials, and that gamma radiation from these elements could penetrate steel casing of the usual thickness. Attention was therefore directed to the construction of an instrument which would record gamma ray intensity within cased boreholes. A paper by Howell and Frosch (1939) describes early work done by the Humble Oil and Refining Company. Their first apparatus employed an ionization chamber as a detector of gamma rays but they soon turned to the use of specially built Geiger counters. Another paper by Green and Fearon (1940) describes similar work by Well Surveys, Inc. Their apparatus employed an ionization chamber as the detecting element. Although this paper gives few details of the instrumentation used, it has an interesting discussion of the rationale of gamma ray logging.

About 1942 a well-logging technique employing a source of neturons was introducted. A detector of gamma rays is located a few feet from a neutron source, (usually a mixture of radium and beryllium), but well shielded from it. Neutrons bombarding the rocks adjacent to the well, produce secondary emission of gamma rays which are registered by the detector. The magnitude of the induced gamma radiation is principally determined by the amount of hydrogen in the vicinity which, in turn, is a function of the porosity and fluid content of the adjacent formations. A paper describing an advanced form of instrumentation for obtaining both neutron and gamma ray logs is that of Swift (1952).

Most well logging methods, although introduced by geophysicists, are primarily tools of the petroleum engineer and of the geologists. The exception is

the relatively new acoustic logging techniques. This method was developed by geophysicists specifically for their own use. To the delight of all concerned, this method now shows promise of being a powerful means of estimating the porosity[3] of formations penetrated by a well, information which is of tremendous interest to petroleum engineers.

A paper by Vogel (1952) of the Shell Oil Company describes a type of apparatus designed specifically to obtain information for the geophysicist. The assembly lowered into a well consists of a sound source (an electric spark), spaced five feet from a piezo-electric detector by an elastic connecting link. The sound source produces a pulse at five foot intervals as the instrument is lowered in a well, and simultaneously sends a time-break signal to the surface through a cable. The detector output is also transmitted to the surface where it is displayed on a cathode ray oscilloscope whose sweep is triggered by the time-break signal. The face of the scope is continuously photographed together with a timing calibration signal, and an indication of the depth. By processing the series of pictures a velocity determination for each five-foot interval can be made. Much other information is available from an examination of the form of the received sound pulses. A modification of the apparatus employing two spaced detectors is also described. The use of two detectors increases the accuracy of velocity determination by minimizing the effect of variations in well diameter.

Summers and Broding (1952) describe more elaborate instrumentation developed by the Magnolia Petroleum Corporation. Their equipment yields a log of interval-travel time plotted against depth of the logging instrument. The sound source is a barium-titanate crystal pulsed some 20 times per second as the logging instrument traverses the well. Either one or two piezo electric crystals are used as receivers. The time-break signals and the outputs of the receivers are transmitted to the surface where the time interval between each time-break and the first break of its associated received signal, is automatically measured by an electronic device and recorded on a chart as a function of depth. Alternatively, the travel time between two spaced detectors may be measured.

The instrumentation described by Summers and Broding is essentially the same as that presently used. Magnetostriction transmitters and transducers may be used instead of barium-titinate crystals, and the recording apparatus usually includes an integrator which sums up the small interval travel times to give total travel time over the entire depth range of the survey.

Instrumentation for two other well-logging techniques is described in a paper by Broding, Zimmerman, Somers, Wilhelm, and Stripling (1952). The first of these is the so-called induction log now in common use. The second is a magnetic log which has not yet been used much.

The instrumentation of the induction log is fairly simple. The sensing ele-

[3] Editor's Note: See Pickett, The Use of Acoustic Logs in the Evaluation of Sandstone Reservoirs, p. 250, this issue.

ment is a long solenoid wound on a core of high permeability material. The coil is lowered into the well and connected in a bridge circuit excited by alternating current. The bridge circuit is a means of measuring the electrical impedance of the coil. This impedance is the vector sum of two components, a resistive component in phase with the exciting current and a reactive component 90 electrical degrees out of phase. These two components are recorded separately as a function of the depth of the logging element. Both components of the impedance are affected by the properties of the material surrounding the solenoid. The resistive component is affected by the electrical conductivity of the formations, the reactive component by the magnetic susceptibility of the formations.

The magnetic logging device is a modification of the airborne, total field magnetometer previously described. When used as a logging instrument, the average value of the earth's field is biased out, permitting the instrument to respond to small changes in the remanent magnetism and the susceptibility of the formations traversed.

BACKWORD

The writer has made an honest effort to review the progress of instrumentation as reflected in the pages of GEOPHYSICS. To keep the paper within bounds he has reluctantly omitted all mention of much ingenious instrumentation designed solely for laboratory and field research. Apologies are hereby extended to those whose contributions may have been overlooked.

A definitive history of this subject may never be written. A thorough-going account would require many months of literature search, much of it in foreign journals; in addition to an examination of much unpublished material not easily available. In this review no particular effort has been made to assign priority for developments.

Much information concerning obsolete instrumentation, not available in GEOPHYSICS, will be found in standard reference books particularly those of Jakosky (1950) and Heiland (1940a). An interesting paper by Heiland (1940b) describes many types of gravimeters not mentioned herein.

ACKNOWLEDGEMENT

The subject of this paper was suggested by our Editor, Dr. L. Y. Faust. Without his kindly urging it would never have been finished. My sincere thanks to my collaborators unaware. These include Kenneth L. Cook, and his predecessors, whose labors produced the Cumulative Index for GEOPHYSICS; also O. J. Ritzmann, who, with his associates, have made pertinent patent information readily available. All writers on geophysical topics will always have reason to be grateful to these men.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 92–94

PRESIDENTIAL ADDRESS*

GEOPHYSICAL PARAMETERS

E. V. McCOLLUM†

The interpretation of geophysical data depends upon physical parameters such as density, velocity, resistivity, and magnetic susceptibilities. Better knowledge of the physical parameters leads to better interpretation.

Of the several important parameters used in geophysics, density may possibly be the most fundamental. Laboratory measurements of density have been made by a variety of methods. One of the most common methods of determining the density of a rock sample is to first weigh the sample in air and then in a liquid such as water or mercury. The results of many such measurements have been published.

However, rock densities in their natural habitat may be different than those shown by laboratory methods due to the great pressures, temperatures, and fluid conditions existing in the earth. Hammer (1950) has presented data suggesting that laboratory densities are less than those determined from gravity measurements made in a mine shaft.

Since the densities of rocks in their natural surroundings are desired, it is possible that borehole logging devices will eventually give the best results. Gilbert (1952) has given data taken down a drilled hole using a vibrating string gravity meter. Baker (1957) and Werner, et al. (1957) have used the absorption and scattering of gamma rays to determine density. Considerable success has already been attained, but greater sensitivity and accuracy should be sought. Perfection of present known methods and the design of other instrumentation would be quite valuable and desirable from many standpoints.

Density is valuable in the interpretation of gravity data. Porosities of rocks may be estimated from densities. Other parameters are closely related to density.

Velocity logging which is essential to seismograph interpretation has been common for many years. Many thousands of velocity logs have been made. Most of the earlier surveys consisted of running a seismometer into a drilled hole and shooting near the surface of the earth. This method gives average or effective velocities. Recent advances have been made in acoustic logging in which interval or actual velocities are determined. Velocities have also been measured in the laboratory, but it is quite likely that the measurements made in the field are better, due to the fact that the data are collected under natural conditions.

Probably more electrical logs have been run than any other type of borehole measurement. Electrical resistivities may be obtained in this manner.

* Presented at the Annual International Meeting, Los Angeles, November 9, 1959.

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As pointed out above, not all of the parameters are independent. For instance, it is well known that velocity is a function of density. The absorption of radioactive rays is also a function of density. Porosity may be obtained within narrow limits from density measurements. Faust (1953) has suggested a relationship between velocity and resistivity. There are several published papers in which the authors suggest that porosity may be derived from velocity logs. Susceptibility measurements depend upon the knowledge of density. Whereas, laboratory measurements have yielded results for the various parameters, it is felt that more accurate data can be obtained from the necessary geophysical instruments lowered into boreholes.

In addition to obtaining the parameters necessary for interpretation, geophysical measurements in boreholes may be used for other purposes. A large amount of subsurface geological correlation is based upon electrical surveys, velocity surveys, and radioactive surveys made in drilled wells. There are good possibilities that future improvement in equipment may lead to the additional use of gravitational devices lowered in boreholes.

Another use for geophysical surveys conducted in drilled wells is that of obtaining data useful in reservoir studies. Reservoir engineers in studying porosity, resistivities, velocities, and other parameters, are enabled to make better predictions as to the presence of petroleum and its amount by the use of well logs.

Most of us are engaged in petroleum exploration. I would like to point out that various types of well logging and a better knowledge of physical parameters obtained therefrom can be successfully utilized in mining exploration. All of the tools mentioned above have their place in an exploration program for valuable minerals other than petroleum. In addition, Levanto (1959) has described a borehole magnetometer that has been used in prospecting for ore.

Another field for the use of better knowledge of physical parameters is in the re-interpretation of old data. Practically every company has a considerable amount of data in its files which is just on the border line of being extremely useful. Through the acquisition of better densities, velocities, etc., interpretations may be possible that will enable an operator to make more intelligent investments.

It is realized that a better determination of physical parameters in boreholes will be fraught with many difficulties. But the rewards will be great. Not only will geophysics contribute to a better knowledge of the earth, but it will be a boon to mankind through the additional discovery of petroleum and other minerals so necessary for a better living standard for everyone.

In summation, we need a greater knowledge of the geophysical parameters of the earth. The best way to obtain these is to make geophysical surveys in boreholes. Such surveys will not only be useful to geophysicists exploring for petroleum and other valuable minerals, but they will contribute to subsurface geology and a better estimate of reserves of petroleum and other valuable miner-

als. Thus, geophysics and geophysicists have a very important role to fill in the future.

In the foregoing, I have touched but briefly on various types of geophysical measurements made in drilled holes. Much progress has been made. Many more authors could have been quoted. However, I firmly feel that there is much more to be accomplished. Not only will exploration geophysics be advanced but such measurements will be useful to geodesy and other allied sciences.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 95–105, 9 FIGS.

CONTINUOUS SIGNAL SEISMOGRAPH*

JOHN M. CRAWFORD,† WILLIAM E. N. DOTY,† AND MILFORD R. LEE†

ABSTRACT

The paper describes a seismic method in which a continuous signal vibrator provides the source energy. Operational features as well as some general theoretical considerations are discussed.

INTRODUCTION

During the past several years, Continental Oil Company's Exploration Research Division has considered some of the problems associated with seismic prospecting from the ground surface. An interesting consequence of this study has been the development of a continuous energy method called "VIBROSEIS,"[1] in which a vibrator replaces dynamite as the energy source. Cross-correlation of the input and received signals provides time resolution of the events and, in addition, enhances the signal/noise at a rate which is proportional to the square root of the total vibration time. A rather formidable computing step is added to the conventional record processing operation, however. The theoretical implications of a completely controllable source operating at the surface are exciting to contemplate, and for this reason they have influenced to a considerable extent our level of effort in this area. This is especially true in view of the practical as well as technical problems which are likely to beset any competing approach which differs markedly from a well-established, successful method.

A variety of field and laboratory equipment has been and is being tested in connection with this method. However, in the interest of clarity, one particular set will be used here in the description of operational procedures.

THE PRINCIPLE OF "VIBROSEIS" EXPLORATION

Searching for an expected signal by the mathematical operation of cross-correlation has been well established as a useful approach. When the characteristics of the searched-for signal are precisely known, it is an extremely powerful technique, and it becomes theoretically possible to establish the presence of signal under any noise condition. "VIBROSEIS" exploration involves the practical application of this principle to geophysical prospecting.

Figure 1 diagrams the method. For simplicity, a single removed detector is shown. The source and detector play the same part as in conventional dynamite shooting, but here the correlator must operate on the detected signal to provide an output which corresponds to the conventional field record.

* Manuscript received by the Editor October 19, 1959.

† Continental Oil Company, Ponca City, Oklahoma.

[1] Trademark of Continental Oil Company.

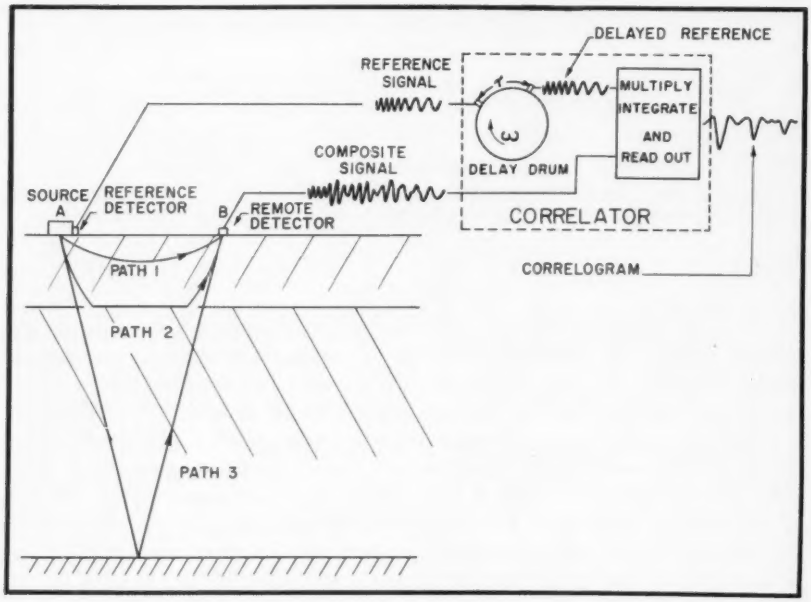

FIG. 1. Diagrammatic illustration of the continuous energy method.

A unique, nonrepeating signal of several seconds duration is introduced by the vibrator source at A, and the composite signal is detected at B in the usual way. However, at this point, few conclusions can be drawn by merely observing the composite signal since, in effect, it is composed of several long-duration signals which overlap in the region of interest. The additional computing step in the form of cross-correlation is introduced to provide the necessary time resolution of events.

Figure 2 demonstrates how the detected signal, or monitor record might look for the three-path case shown in Figure 1. For convenience, the signals used in the illustration are of much shorter time duration than those used in the field.

If it were possible to monitor the individual signals corresponding to the separate paths, Example A would be the result, assuming ideal conditions. The three signals are identical in content, but are displaced from the reference (input) signal according to the individual travel times along those three paths. Example B is just the addition of the signals in A. Even in this very simple case, the complexity of the composite signal prevents a quick observational reconstruction of the initial conditions. In an actual field case, the problem is even more acute and

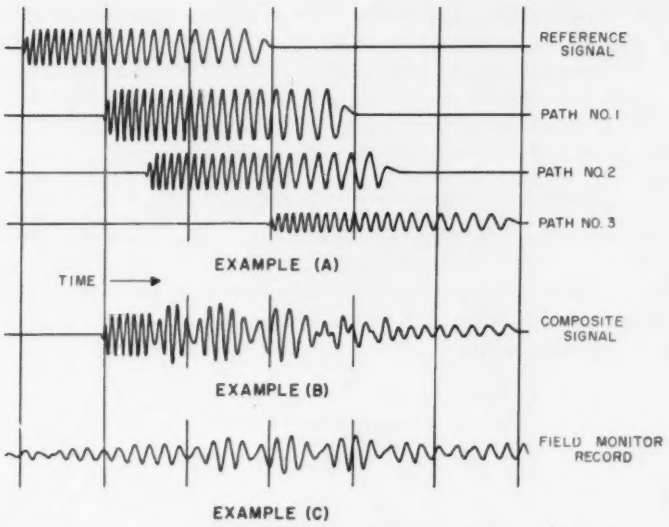

FIG. 2. Examples (A) and (B) are laboratory simulations of a three path case. Example (C) is a segment of an actual field monitor record.

is demonstrated in Example C. Subsequent cross-correlation with the reference signal automatically ascribes the proper time, amplitude, and polarity to each path present in that composite monitor record. In performing this operation, the mathematical problem to be solved is

$$\Phi_{gr}(\tau) = \frac{1}{T}\int_0^T r(t)g(t+\tau)dt,$$

where $g(t)$ and $r(t)$ are the generated and received signals. This function is susceptible to analog solution; and, as shown in Figure 1 the correlator consists of a delay drum, a multiplier-integrator circuit, and a readout device. A more specific description of the equipment is given later in the paper. The dimensions of the plot, $\Phi_{gr}(\tau)$ versus τ, are the same as those of a seismograph trace, and the maxima of that correlogram correspond to the events on the equivalent seismograph record. Refer again to Figure 1 and suppose that only path number 1 exists whose travel time is T_1. In the process of obtaining the correlogram, the delay drum is incrementally adjusted through values of $\tau=0$ to $\tau=T$ where T is the greatest penetration time of interest. When the delay time exactly equals the travel time T_1, $\Phi_{gr}(\tau)$ is a maximum. In this idealized case, if no noise is present, $\Phi_{gr}(\tau)$ is simply the autocorrelation function which has a shape very similar to a

Ricker wavelet of the same band-width. This is the reason the method produces a record very similar in appearance to the equivalent shot record. Although the geophysical interpretation is carried out in the usual manner, one obvious difference exists. The continuous energy method provides no high frequency "first break." Each arrival is represented by a symmetrical wavelet whose center trough (or peak) indicates the corresponding travel time.

CHOICE OF INPUT SIGNAL

A short, generalized discussion of signal spectrum effects will demonstrate the desirable features (theoretical) of the method and at the same time lead to an introduction of some of the physical, as well as engineering problems encountered. Knowing the connection between signal content and correlation wavelet shape provides the starting point.

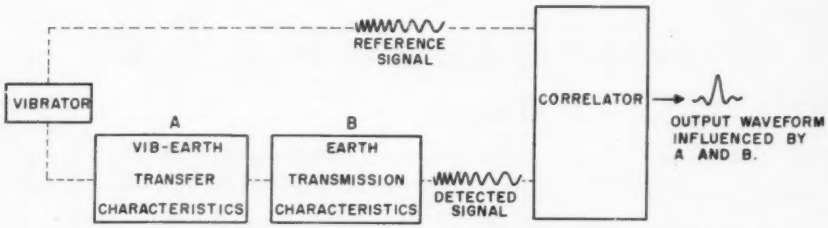

FIG. 3. Block diagram showing external factors which affect the correlation wavelet shape.

Ideally, in a nondistorting medium, it is possible to control the wave shape of a particular reflection event. Actually earth characteristics, primarily, limit the amount of exercisable control although engineering difficulties of some consequence have been encountered. Figure 3 illustrates the role of troublesome earth effects in the method.

The combined effect of factors *A* and *B* is to distort the intended signal and as a consequence the resulting correlation wavelet does not have the anticipated shape. Complete compensation for these bothersome earth properties is difficult for a variety of reasons. A comparison with the shot technique, however, does illustrate the relative degree of control which may be brought to bear. Even though a dynamite blast may generate a very wide band of frequencies, differential attenuation or dissipation by the earth reduces the detected wavelet to a rather limited band-width. While it is true that usual "VIBROSEIS" practice is to generate only those frequencies which the earth does not severely attenuate, considerable control can be exercised within that band. This is made possible by the fact that the method operates in the time domain. Figure 4 provides a simplified demonstration of this feature.

First, suppose that amplitude attenuation constitutes the primary distorting

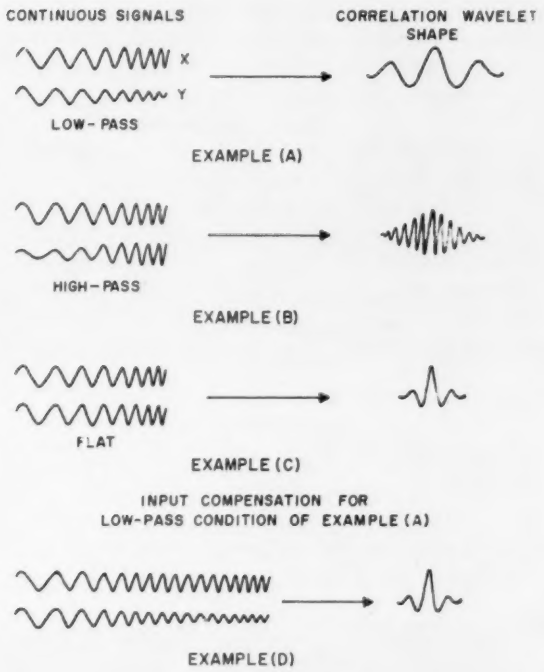

FIG. 4. Approximate effect of amplitude attenuation on the correlation wavelet. Example (D) demonstrates input compensation for this simplified case.

effect. Examples (A) through (C) illustrate the possible consequences. The undistorted reference signal and its appearance (minus noise) after having traversed some earth path are shown as traces X and Y respectively in Example (A). Upon cross-correlation of the two signals, the low frequencies will obviously dominate in the correlation wavelet since the process involves the point-by-point multiplication of the two functions. On the other hand, Example (B) shows the situation when the lower frequencies are attenuated relatively more. The low apparent frequency of the wavelet in the low-pass case results in a loss of resolution; whereas, any gain in that direction supplied by the higher frequency of Example (B) is overshadowed by the loss in definition. The exact same fate would be suffered by a dynamite pulse having the same input spectrum, and filtering would be of help only within the particular frequency band where adequate signal-to-noise ratio has been established. Whatever the shape of the correlation wavelet, it serves as the building block in this continuous energy method. The final correlogram is composed of one correlation wavelet per earth path, each having its proper time, amplitude, and polarity.

Earth transmission characteristics prevent all wavelets making up a particular trace from having the exact same shape. The apparent frequency of the correlation wavelet depends not only on the relative amplitudes of the various frequencies (for flat input), but also upon the relative number of cycles of each frequency present in the continuous signal. Consider again Example (A) of Figure 4 which may approximate some real condition. Compensation for the low-pass earth characteristic can be made by generating an input signal which is relatively rich in high frequency content as illustrated in Example (D). Theoretically inherent in the method, therefore, is a means for minimizing certain unalterable attenuation characteristics of the earth where those properties might otherwise be detrimental. The possibility of extending this simple illustration to more complicated situations may be inferred by considering the equivalence of cross-correlation and filtering which has been adequately reported elsewhere (Jones and Morrison 1954).

EQUIPMENT

The vibrator and correlator represent the only complete departures from conventional seismograph equipment. The magnetic recorder and detecting instruments are substantially the same as those used on conventional crews, although the recording speed has been reduced to allow a longer recording period. Figures 5, 6, and 7 show the vibrator equipment in three poses. The vibrator

FIG. 5. Vibrator trailer in its normal operating position.

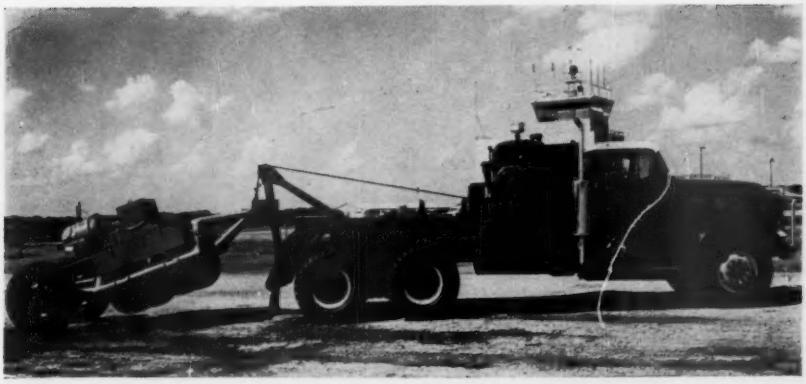

FIG. 6. Vibrator and tow truck ready for move of moderate distance.

trailer is in operating position in Figure 5, while in Figure 6 it has been racked into trail position for intermediate distance hauls on the project. Figure 7 shows the whole assembly secured for highway travel. Notice when in vibrate position the unit rolls on large steel wheels and is towed to the various positions making up the source pattern. Off-center weights inside the centrally located box provide a thrust which is proportional to the square of the instantaneous frequency and is confined to the vertical direction. This is a typical centrifugal vibrator in which horizontal forces are cancelled between the two properly phased eccentrics. Power necessary to drive the shock-mounted dc motor is cabled back from a gas-electric set mounted on the tow truck. Vibrational output is obtained by causing the direct-coupled vibrator shaft to sweep through the desired frequency band. The frame of the assembly is rigid in order that amplitude and phase of the vibrator

FIG. 7. Vibrator assembly secured for highway travel.

FIG. 8. Multi-channel correlator.

proper will be faithfully transferred through the steel rollers to the earth. The output must be continuously sampled and recorded for subsequent use in the cross-correlation stage of the process. Reference signal detection is accomplished with a modified seisphone mounted directly on the vibrator base plate whose output is sent directly to the recording truck. Everything else helps provide the necessary weight, rigidity, and mobility.

All field recordings are on magnetic tape and are taken at low speed for two primary reasons. Both a relatively long recording time and a data processing speed-up are highly desirable. To appreciate this point, remember that in cross-correlating signals $\Phi_g(t)$ and $\Phi_r(t)$, they must be scanned over their entire duration for each value of delay time τ. For frequencies up to 100 cps, three and one third millisecond intervals for τ are adequate. Even so, 300 separate settings of the delay drum are necessary to compute the record to a penetration of one second, and the correlator input tape must be completely scanned for each setting of τ. This handicap has been minimized by storing several field records in parallel (for simultaneous correlation) on each tape and using a record-playback speed-up of 20 to 1. In addition, two time zones may be computed simultaneously.

From right to left in Figure 8 are the input drum and amplifiers, multi-channel delay drum, operators console, power supplies, two racks of multiplier-integrators, and three pieces of readout equipment. Barely visible to the right of the visual monitor is the magnetic readout drum.

After the operator has completed the initial setup, the equipment automatically sequences and reads out values of $\Phi_{gr}(\tau)$. The filtered playback of $\Phi_{gr}(\tau)$

versus τ then becomes the resultant trace, with zero time corresponding to the point $\tau = 0$.

FIELD PROCEDURE

Fixed cost and mobility are two of the most attractive features of any mechanical energy source. Any method employing such a source should, therefore, enjoy its greatest relative advantage in areas where it has been found necessary to employ large source and detector patterns. In the case of the method being described, pattern shooting is desirable even in regions where interference would present no problem to an impulse system. This is dictated by the long time duration of the input signal. Since that duration is longer than any expected reflection time, the signals returning from all paths are overlapping to some extent. Practical considerations necessitate minimizing the amplitude ratios of these various signals. Toward this same end an in-line offset-type layout is used in order to take advantage of geometry as well as surface wave behavior (Neitzel, 1958). Vibrator positions within the source pattern are occupied sequentially with the individual records being subsequently composited. Since a reference signal is obtained at each position, the question of time correction between positions does not arise. This is an inherent feature of correlation.

In working difficult areas, a considerably greater level of effort can be obtained with a mobile source by transposing the role of source and detector. This field practice is consistently employed in the weight-dropping technique (Waldie 1956). Since considerable vibration time is necessary to establish adequate signal-to-noise ratio, it makes little difference economically whether the vibrator occupies one or many positions—provided the unit is sufficiently mobile. Thus, signal to interference ratio can be improved by occupying a pattern while generating a certain total time of signal required for signal-to-noise ratio.

Weathering corrections present the same problems as they do in any other surface method. In those areas where weathering control appeared necessary, some standard technique has been applied. For example, the surface-to-surface first arrival method is completely satisfactory in places where regular, shallow weathering conditions prevail. On the other hand, when the weathering is erratic or deep, it may be necessary to obtain up-hole times at the points of question. In those cases where a very thick, low velocity problem exists, divergence mapping may provide the most realistic interpretation. This, of course, depends on the ability to map a consistent shallow reflection. The method enjoys some advantage in this regard in that the first arrivals are not large enough to obscure much of the shallow reflection zone. This is a feature of the offset-pattern recording procedures.

CONCLUSIONS

As stated at the outset, the theoretical implications of some aspects of the continuous energy method are extremely attractive. Attractive enough, to

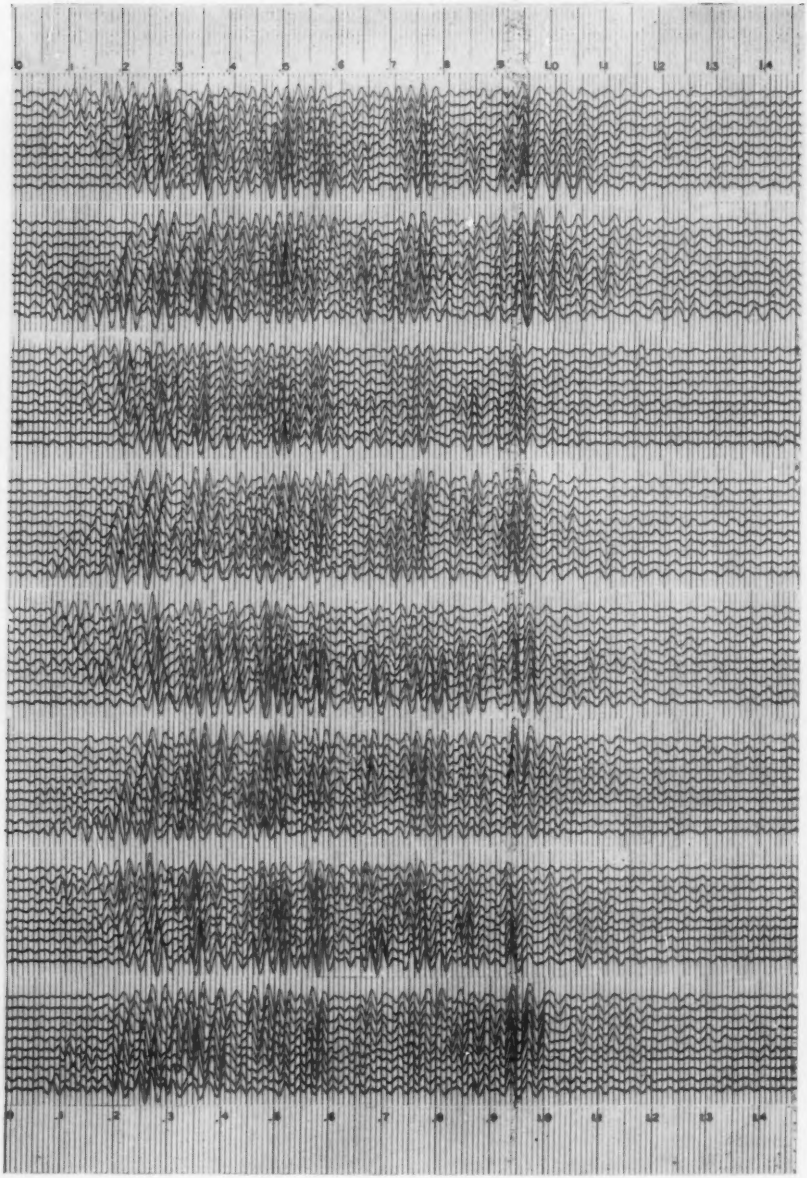

FIG. 9. Continuous energy method record section.

warrant considerable effort in trying to determine the realizable advantages. Results so far have encouraged us to continue to pursue the method. Being a seismic technique, "VIBROSEIS" exploration is restricted in application to seeking acoustic contrasts, and in that sense, suffers the same limitations as conventional seismograph.

Figure 9 is a record section obtained with this method.

The authors are grateful to Continental Oil Company for granting permission to present the general features of this development.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 106–129, 11 FIGS.

SEISMOGRAM SYNTHESIS INCLUDING MULTIPLES AND TRANSMISSION COEFFICIENTS*

P. C. WUENSCHEL†

ABSTRACT

Synthetic seismograms that include multiples and transmission coefficients have been obtained by solving the boundary value problem for the multilayered half-space exactly for the plane wave case at normal incidence. The computations of four seismograms of interest have been programmed for the IBM 704. The seismograms differ in location of source and detector, i.e., whether buried or at the surface of the half-space and whether or not this surface is a stress-free surface. Evaluation of the computer programs prior to synthesizing seismograms is accomplished by comparing computer with analytical solutions of simple problems.

The significance of multiples to the total reflected signal depends on the vertical distribution of acoustic impedance. For small contrasts in acoustic impedance distributed throughout the section, multiples are relatively insignificant. For moderate contrasts similarly distributed, multiples can produce discrete events, cause phase shifts in large amplitude direct reflections, and alter the frequency of weak direct reflected signal. If the near-surface contrasts are large, then multiples within these layers can mask a direct reflected signal from depth by producing "ringing" or "wave training." The present analysis gives a more reasonable explantion of "ringing" records than has been given heretofore. It is evident when comparing synthetic seismograms, including multiples with field seismograms, that the predicted multiple contribution in many cases is greater than actually present, indicating that the mathematical model on which computation is based is not yet adequately realistic.

INTRODUCTION

The advent of the continuous velocity log and the electronic computer, both analogue and digital, has afforded an opportunity to obtain a detailed knowledge of the reflected signal recorded on the reflection seismogram.

Peterson and his co-workers (1955) were the first to use these new tools to predict the reflected signal. Despite the fact that their technique involves several assumptions and approximations, the synthetic seismograms produced agree very well in many cases with the reflection signal on the field seismograms.

In some cases, however, the agreement is poor despite the good quality of the reflection record. This poor agreement can be caused partly by the fact that the synthetic seimogram produced by Peterson's method approximates the true reflected signal. An improvement in the agreement would be expected if the approximations used by Peterson could be removed.

The purpose of this paper is to remove, partially, the approximations Peterson used to compute the reflected signal from the multilayered medium. His technique consists in neglecting transmission coefficients and multiples and to approximate the reflection coefficient at each change in acoustic impedance by using one-half the difference of the logarithm of the velocity across the contrast.

The technique discussed in this paper includes multiples and transmission coefficients by computing exactly the reflected signal recorded at the surface of a

* Presented at the twenty-eighth Annual Meeting, San Antonio, October 16, 1958. Manuscript received by the Editor February 6, 1959.

† Gulf Research and Development Company, Pittsburgh, Pa.

multilayered half-space due to a source of plane waves at normal incidence to the surface for the case where the source behaves as a unit impulse in time.

In addition to solving this problem, it is also possible, with slight algebraic manipulation, to obtain solutions to other problems of interest to reflection seismology, such as the determination of the detector signal for a surface or buried detector due to a buried source and the determination of the importance of the stress-free surface in producing multiples.

In all, four problems of interest have been programmed: surface source-surface detector with and without the stress-free surface, surface source-buried detector, and buried source-buried detector. The latter two problems have the free surface present. The program for each problem, as initially written, will accomodate 800 layers and if run separately, would require 20 minutes each. Currently the problems are being combined into a single program that can solve from one to all four problems during a single run and will accommodate 1,850 layers.

In this paper the programs completed will be evaluated by comparing the computer results with the analytical results obtained for three simple velocity distributions. Some of the programs will then be used to compute the exact synthetic seismograms (for the plane wave case) for velocity distributions as given by the continuous velocity logs. These synthetic seismograms are compared with the approximate synthetic seismograms as computed by using Peterson's technique and together are compared with field records taken near the well. Examples are chosen which demonstrate the velocity distribution for which the contribution of multiples varies from insignificance to a degree where multiples smooth and distort the direct reflected signal beyond recognition—the latter example being the "ringing" record. As a consequence of the successful prediction of "ringing" records by methods described here, a better understanding of their cause is possible than is provided by existing theories.

The new computational technique discussed here does not give the most accurate prediction of the reflected signal possible, for in practice a point source rather than a plane wave source is used; the nature of the layered media is not perfectly elastic, but possesses dissipation and the bounding interfaces of the layers are not necessarily smooth and parallel but may be rough and nonparallel.

THEORY

The various problems of interest involve the computation of the detector signal, particle velocity or stress, at a specific location within or at the surface of a multilayered half-space due to a unit impulse source at the same or different locations within or at the surface of the multilayered media. The detector signal for a source behaving as an arbitrary function of time can be obtained by convolution.

To express the detector signal in terms of the source function, a boundary value problem involving N layers and $N+1$ interfaces must be solved. There are several ways to accomplish this (see for example Berryman, et al., 1958). The

method chosen here uses the matrix formulation introduced into the literature by W. T. Thomson (1950).

To simplify the problem we will consider a horizontally layered medium, Figure 1, composed of layers of homogeneous, isotropic and ideally elastic material of velocity c and density ρ. The half-space opposite the layered media will be taken either as vacuum or as a homogeneous half space. Propagation in one direc-

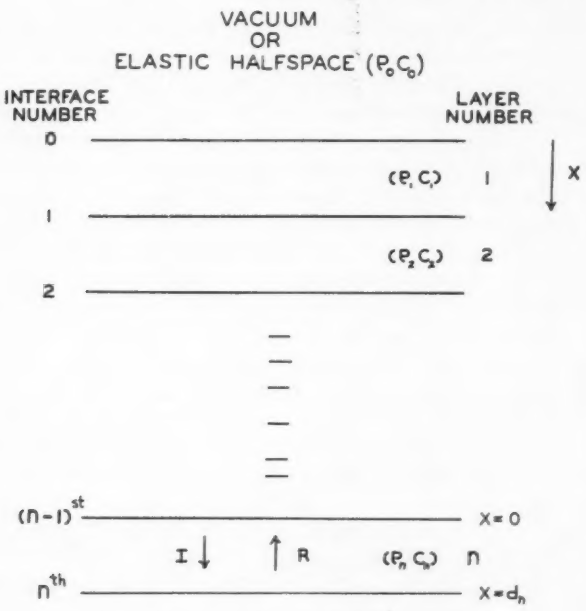

FIG. 1. Multilayered half-space.

tion only will be considered, namely, plane wave propagation at normal incidence to the stratification. The positive x direction is taken into a stratified medium.

The wave equation to be solved in each layer is

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}, \tag{1}$$

where u is the particle displacement within the layer, c is the compressional velocity characteristic of the layer.

The solution must satisfy the boundary conditions for the layer, namely, that the particle velocity and stress be continuous across each interface between layers and further, subject to the initial conditions at the source. The initial conditions will vary, depending on the specific problem to be solved.

Applying operational methods (1) becomes

$$\frac{\partial^2 \bar{u}}{\partial x^2} = \frac{s^2}{c^2}\,\bar{u}, \tag{2}$$

where the bar over a variable represents the Laplace transform of the variable defined as:

$$\bar{u} = \int_0^\infty u e^{-st} dt.$$

The particle displacement satisfying (2) for the nth layer is:

$$\bar{u}_n = I e^{-sz/c_n} + R e^{sz/c_n}, \tag{3}$$

where the first and second term of the right-hand member represents a wave traveling in the positive and negative x direction, respectively. The amplitudes of each of these waves, namely I and R, are complex and are functions of frequency and of transit time for a compressional disturbance to cross the layer.

The particle velocity and stress for the nth layer are

$$\begin{aligned} \bar{\dot{u}}_n &= I s e^{-sz/c_n} + R s e^{sz/c_n}, \\ \bar{\sigma}_n &= -\rho_n c_n I s e^{-sz/c_n} + \rho_n c_n R s e^{sz/c_n}. \end{aligned} \tag{4}$$

Choosing the origin of the x coordinate in the $(n-1)$st interface and assigning $x = d_n$ to the nth interface, the particle velocity and stress of the bounding interfaces of the nth layer are

$$\begin{aligned} \bar{\dot{u}}_{n-1} &= s(I + R), \\ \bar{\sigma}_{n-1} &= \rho_n c_n s(-I + R), \\ \bar{\dot{u}}_n &= I s e^{-sd_n/c_n} + R s e^{sd_n/c_n}, \\ \bar{\sigma}_n &= -\rho_n c_n I s e^{-sd_n/c_n} + \rho_n c_n R s e^{sd_n/c_n}. \end{aligned} \tag{5}$$

After some manipulation, equation (5) can be written in the following matrix form

$$\begin{vmatrix} \bar{\dot{u}}_n \\ \bar{\sigma}_n \end{vmatrix} = \begin{vmatrix} s\left(\dfrac{e^{sd_n/c_n} + e^{-sd_n/c_n}}{2}\right) & -s\left(\dfrac{e^{sd_n/c_n} - e^{-sd_n/c_n}}{2}\right) \\ \rho_n c_n s\left(\dfrac{e^{sd_n/c_n} - e^{-sd_n/c_n}}{2}\right) & -\rho_n c_n s\left(\dfrac{e^{sd_n/c_n} + e^{-sd_n/c_n}}{2}\right) \end{vmatrix} \begin{vmatrix} (I + R) \\ (I - R) \end{vmatrix}, \tag{6}$$

$$\begin{vmatrix} \bar{\dot{u}}_{n-1} \\ \bar{\sigma}_{n-1} \end{vmatrix} = \begin{vmatrix} s & 0 \\ 0 & -\rho_n c_n s \end{vmatrix} \begin{vmatrix} (I + R) \\ (I - R) \end{vmatrix}.$$

Inverting the second equation of (6) and substituting it into the first equation of (6) yields

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n| \begin{vmatrix} \bar{u}_{n-1} \\ \bar{\sigma}_{n-1} \end{vmatrix}, \tag{7}$$

where

$$|\alpha_n| = \begin{vmatrix} \left(\frac{e^{sd_n/c_n} + e^{-sd_n/c_n}}{2}\right) & \frac{1}{\rho_n c_n}\left(\frac{e^{sd_n/c_n} - e^{-sd_n/c_n}}{2}\right) \\ \rho_n c_n \left(\frac{e^{sd_n/c_n} - e^{-sd_n/c_n}}{2}\right) & \left(\frac{e^{sd_n/c_n} + e^{-sd_n/c_n}}{2}\right) \end{vmatrix}. \tag{8}$$

Equation (7) relates the particle velocity and stress of the $(n-1)$st interface to the particle velocity and stress at the nth interface. Since the particle velocity and stress are continuous across the $(n-1)$st interface between the nth and $(n-1)$st layer, then we write

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n||\alpha_{n-1}| \begin{vmatrix} \bar{u}_{n-2} \\ \bar{\sigma}_{n-2} \end{vmatrix}. \tag{9}$$

The process can be continued to the zeroth interface yielding

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n| \cdots |\alpha_1| \begin{vmatrix} \bar{u}_0 \\ \bar{\sigma}_0 \end{vmatrix}. \tag{10}$$

If the particle velocity or stress is not continuous across the ath interface due to the placement of the source at this location, then (10) can be written

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n| \cdots |\alpha_{a+1}| \begin{vmatrix} \bar{u}_{a+} \\ \bar{\sigma}_{a+} \end{vmatrix},$$

$$\begin{vmatrix} \bar{u}_{a-} \\ \bar{\sigma}_{a-} \end{vmatrix} = |\alpha_a| \cdots |\alpha_1| \begin{vmatrix} \bar{u}_0 \\ \bar{\sigma}_0 \end{vmatrix}, \tag{10a}$$

where $(a+)$ and $(a-)$ represent the positive and negative sides of the ath interface. The relationship between the velocity and stress at the ath interface will be given by the source specification.

SOURCE AND DETECTOR AT THE UPPER SURFACE OF THE LAYERED MEDIA

If the source is placed at the upper surface of the layered media, then (10a) can be written as

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n| \cdots |\alpha_1| \begin{vmatrix} \bar{u}_{0+} \\ \bar{\sigma}_{0+} \end{vmatrix}. \tag{11}$$

For a "concentrated" source, the particle velocity is continuous across the zeroth interface while the stress below and above the interface differs by the time variation of the source which we will take as the unit impulse function, $\delta(t)$. In the time domain, these conditions are

$$\begin{aligned} \dot{u}_{0+} &= \dot{u}_{0-} \\ \sigma_{0+} - \sigma_{0-} &= -\delta(t) \end{aligned} \tag{12}$$

and in the transform domain these become

$$\begin{aligned} \bar{\dot{u}}_{0+} &= \bar{\dot{u}}_{0-} \\ \bar{\sigma}_{0+} - \bar{\sigma}_{0-} &= -1. \end{aligned} \tag{13}$$

Substituting from (13) to (11) and neglecting the sign subscript for the particle velocity, we have

$$\begin{vmatrix} \bar{\dot{u}}_n \\ \bar{\sigma}_n \end{vmatrix} = |\alpha_n| \cdots |\alpha_1| \begin{vmatrix} \bar{\dot{u}}_0 \\ \bar{\sigma}_{0-} - 1 \end{vmatrix}. \tag{14}$$

Since our velocity and density information is limited in depth to the $(N+1)$st layer, the detector signal can be computed only for the time interval between the shot instant and the time required for the transit of a compressional disturbance to travel from the source to the Nth interface and back to the detector. Since the velocity distribution below the $(N+1)$st layer does not enter the computation $\bar{\dot{u}}_n$ and $\bar{\sigma}_n$ can be expressed in terms of the transmitted wave into the $(N+1)$st layer giving for (14)

$$\begin{vmatrix} \bar{\dot{u}}_t \\ -\rho_{N+1}c_{N+1}\bar{\dot{u}}_t \end{vmatrix} = |\alpha_N| \cdots |\alpha_1| \begin{vmatrix} \bar{\dot{u}}_0 \\ \bar{\sigma}_{0-} - 1 \end{vmatrix}. \tag{15}$$

Forming the product of the matrices and eliminating $\bar{\dot{u}}_t$ (15) becomes

$$\bar{\dot{u}}_0 = \frac{\dfrac{A_{22}}{\rho_{N+1}c_{N+1}} + A_{12}}{A_{11} + \dfrac{A_{21}}{\rho_{N+1}c_{N+1}}} (-(\bar{\sigma}_{0-} - 1)), \tag{16}$$

where

$$\begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix} = |\alpha_N| \cdots |\alpha_1|. \tag{17}$$

If the upper surface of the layered medium is the stress-free surface, $\sigma_{0-}=0$ and likewise its transform which allows (16) to be written simply,

$$\bar{u}_0 = \frac{\dfrac{A_{22}}{\rho_{N+1}c_{N+1}} + A_{12}}{A_{11} + \dfrac{A_{21}}{\rho_{N+1}c_{N+1}}} . \tag{18}$$

If the upper surface is not the free surface, and if the half-space opposite the layered half-space is homogeneous and of characteristic impedance $\rho_0 c_0$, then $\bar{\sigma}_{0-}$ can be written in terms of the particle velocity of the wave traveling in the negative x direction into the homogeneous half-space giving for (16)

$$\bar{u}_0 = \frac{\dfrac{A_{22}}{\rho_{N+1}c_{N+1}} + A_{12}}{A_{11} + \dfrac{A_{21}}{\rho_{N+1}c_{N+1}} + \rho_0 c_0 \left(\dfrac{A_{22}}{\rho_{N+1}c_{N+1}} + A_{12} \right)} . \tag{19}$$

Equations (18) and (19) are the desired results, expressing the particle velocity in terms of the forcing function of the source with a single factor of proportionality which is a function of the characteristic impedances of the individual layers and the transit time across the layers. The function is a ratio of elements of the product matrix defined in (17) where each matrix is defined by (8). If the layer thicknesses are adjusted in accordance with the layer velocities so that the transit time across the layer is a constant, i.e.,

$$\frac{d_{n-i}}{c_{n-i}} = \tau, \qquad (i = 0, \cdots, n-1) \tag{20}$$

equation (8) can be written as

$$|\alpha_n| = \frac{e^{s\tau}}{2} \begin{vmatrix} (1 + e^{-2s\tau}) & \dfrac{1}{\rho_n c_n}(1 - e^{-2s\tau}) \\ \rho_n c_n (1 - e^{-2s\tau}) & (1 + e^{-2s\tau}) \end{vmatrix} . \tag{21}$$

The elements of the product matrix defined by (17) can then be expressed as a polynomial in $e^{-2s\tau}$. The particle velocity $\bar{u}_0$, equations (18) and (19), is then the ratio of two polynomials which can be expressed as

$$\bar{u}_0 = a_0 + a_1 e^{-2s\tau} + a_2 e^{-4s\tau} + \cdots + a_N e^{-2Ns\tau}, \tag{22}$$

where the coefficients a_n are functions of the characteristic impedances of the individual layers.

The inverse transform of (22) recovers the time function u_0 which is

$$u_0 = a_0 \delta(t) + a_1 \delta(t - 2\tau) + \cdots + a_N \delta(t - 2N\tau). \tag{23}$$

Thus, if the stress pulse source is a unit impulse in time, the particle velocity is a series of unit impulses separated in time given by twice the transit time across

each of the layers and whose magnitudes (or strengths) are determined by the characteristic impedances of the appropriate layers.

SOURCE BURIED AND DETECTOR AT THE UPPER SURFACE OF THE LAYERED MEDIA

The expression for the particle velocity in this case follows directly from equation (10a). The boundary and initial conditions of the ath interface, following Pekeris (1948), are that the stress should be continuous, i.e.,

$$\sigma_{a+} = \sigma_{a-},$$

but the particle velocity above and below the ath interface moves in opposite directions. In the time domain, this motion will be described by the unit impulse as follows:

$$\dot{u}_{a+} - \dot{u}_{a-} = \delta(t).$$

In the transform space these conditions become

$$\begin{aligned} \bar{\sigma}_{a+} &= \bar{\sigma}_{a-} \\ \bar{u}_{a+} - \bar{u}_{a-} &= 1. \end{aligned} \tag{24}$$

Substituting from (24) into (10a) and regrouping we have

$$\begin{vmatrix} \bar{u}_n \\ \bar{\sigma}_n \end{vmatrix} = \begin{vmatrix} \alpha_n \end{vmatrix} \cdots \begin{vmatrix} \alpha_1 \end{vmatrix} \begin{vmatrix} \bar{u}_0 \\ \bar{\sigma}_0 \end{vmatrix} + \begin{vmatrix} \alpha_n \end{vmatrix} \cdots \begin{vmatrix} \alpha_{a+1} \end{vmatrix} \begin{vmatrix} 1 \\ 0 \end{vmatrix}. \tag{25}$$

Representing $\bar{u}_n$ and $\bar{\sigma}_n$ in terms of the transmitted wave into the $(N+1)$st layer, and $\bar{u}_0$ and $\bar{\sigma}_0$ in terms of the transmitted wave into the half-space $\rho_0 c_0$, we have

$$\begin{vmatrix} \bar{u}_t \\ -\rho_{N+1}c_{N+1}\bar{u}_t \end{vmatrix} = \begin{vmatrix} A_{11}\bar{u}_0 + \rho_0 c_0 A_{12}\bar{u}_0 + A_{11}' \\ A_{21}\bar{u}_0 + \rho_0 c_0 A_{22}\bar{u}_0 + A_{21}' \end{vmatrix}, \tag{26}$$

where

$$\begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix} = \begin{vmatrix} \alpha_N \end{vmatrix} \cdots \begin{vmatrix} \alpha_1 \end{vmatrix}$$

$$\begin{vmatrix} A_{11}' & A_{12}' \\ A_{21}' & A_{22}' \end{vmatrix} = \begin{vmatrix} \alpha_N \end{vmatrix} \cdots \begin{vmatrix} \alpha_{a+1} \end{vmatrix}.$$

Eliminating $\bar{u}_t$ and solving for $\bar{u}_0$ in equation (26), we have

$$\bar{u}_0 = -\frac{A_{11}' + \dfrac{A_{21}'}{\rho_{N+1}c_{N+1}}}{A_{11} + \dfrac{A_{21}}{\rho_{N+1}c_{N+1}} + \rho_0 c_0 \left(A_{12} + \dfrac{A_{22}}{\rho_{N+1}c_{N+1}} \right)}. \tag{27}$$

If the zeroth interface is a stress-free surface, $\rho_0 c_0$ is zero and (27) becomes

$$\bar{\dot{u}}_0 = -\frac{A_{11}' + \dfrac{A_{21}'}{\rho_{N+1}c_{N+1}}}{A_{11} + \dfrac{A_{21}}{\rho_{N+1}c_{N+1}}}. \tag{28}$$

Using the same procedure on (27) and (28) that was used to convert equation (18) and (19) into the form of equation (23), we have

$$\dot{u}_0 = a_0\delta(t - a\tau) + a_1\delta(t - (a+2)\tau) + \cdots + a_N\delta(t - (a+2N)\tau). \tag{29}$$

Thus, for a buried source behaving as a unit impulse in time, the particle velocity at the surface consists of a series of unit impulses delayed at equal intervals of time given by 2τ seconds. The first pulse reaching the surface is delayed $a\tau$ seconds after the "shot instant." The magnitude of the pulses is determined by the characteristic acoustic impedances, $\rho_n c_n$, of the layered media.

SOURCE AT THE UPPER SURFACE OF THE LAYERED MEDIA OR BURIED—DETECTOR BURIED

To determine the particle velocity and stress for the buried detector, we simply invoke the relationship given by (10) and (10a), namely, if the particle velocity and stress are known at any one interface of a layered media, they can be determined at any other.

If the source is at the surface, i.e., the zeroth interface, and the detector is at the bth interface, and the particle velocity at the zeroth interface, $\bar{\dot{u}}_0$, for N layers is known, then from (14)

$$\begin{vmatrix} \bar{\dot{u}}_b \\ \bar{\sigma}_b \end{vmatrix} = |\alpha_b| \cdots |\alpha_1| \begin{vmatrix} \bar{\dot{u}}_0 \\ \bar{\sigma}_{0-} - 1 \end{vmatrix}, \tag{30}$$

or writing

$$\begin{vmatrix} A_{11}'' & A_{12}'' \\ A_{21}'' & A_{22}'' \end{vmatrix} = |\alpha_b| \cdots |\alpha_1|, \tag{31}$$

we have

$$\begin{vmatrix} \bar{\dot{u}}_b \\ \bar{\sigma}_b \end{vmatrix} = \begin{vmatrix} (A_{11}'' + \rho_0 c_0 A_{12}'')\bar{\dot{u}}_0 - A_{12}'' \\ (A_{21}'' + \rho_0 c_0 A_{22}'')\bar{\dot{u}}_0 - A_{22}'' \end{vmatrix}. \tag{32}$$

If the source is buried at interface a with the detector at interface b, then using (25) we have

$$\begin{vmatrix} \bar{u}_b \\ \bar{\sigma}_b \end{vmatrix} = |\alpha_b| \cdots |\alpha_1| \begin{vmatrix} \bar{u}_0 \\ \bar{\sigma}_0 \end{vmatrix} + |\alpha_b| \cdots |\alpha_{a+1}| \begin{vmatrix} 1 \\ 0 \end{vmatrix}, \tag{33}$$

writing

$$\begin{vmatrix} A_{11}''' & A_{12}''' \\ A_{21}''' & A_{22}''' \end{vmatrix} = |\alpha_b| \cdots |\alpha_{a+1}|, \tag{34}$$

and with (31) we have

$$\begin{vmatrix} \bar{u}_b \\ \bar{\sigma}_b \end{vmatrix} = \begin{vmatrix} (A_{11}'' + \rho_0 c_0 A_{12}'')\bar{u}_0 + A_{11}''' \\ (A_{21}'' + \rho_0 c_0 A_{22}'')\bar{u}_0 + A_{12}''' \end{vmatrix}. \tag{35}$$

The particle velocity and stress at the bth interface can be obtained from (32) or (35), depending on the location of the source. If the upper surface of the layered media is a stress-free surface, then $\rho_0 c_0$ in (32) and (35) are set equal to zero.

UTILIZATION OF THE THEORY

The results for the source and detector at the stress-free surface, Equation (18), and at the upper surface of the layered space (19), the buried source-surface detector problem (28), and the buried source-buried detector problem with $\rho_0 c_0 = 0$ (35) have been programmed for the IBM 704 by Mrs. Ruby McKelvey under the supervision of Drs. E. B. Weinberger and D. S. Hoffman of the Computational Analysis Section of our Laboratory.

The programs, as originally written, will accommodate 800 layers, and each program requires 20 minutes computer time. Currently, the programs are being combined and provision is being made for 1,850 layers.

EVALUATION OF THE PROGRAMS

In order to test the programs for their reliability and accuracy, three test problems were used. The first two programs, i.e., source and detector at the upper surface of a layered half-space with $\rho_0 c_0$ equal and not equal to zero, were used on the first two problems while three of the programs, all of which include the stress-free surface, were used in the third problem.

The first problem consisted merely of three identical layers with a velocity of 12,000 ft per sec, embedded in a medium with a velocity of 8,000 ft per sec. The density is considered constant throughout and taken as unity. The layers (Figure 2A) are separated vertically such that multiples between the layers would not interfere with the reflection from the layers themselves. In the program having the stress-free surface, the layers were buried at a depth below the surface so that surface induced multiples would not interfere with the direct reflection. In the program where the stress-free surface is not present, this precaution was not taken. The results of both programs were identical and are shown in Figure 2B.

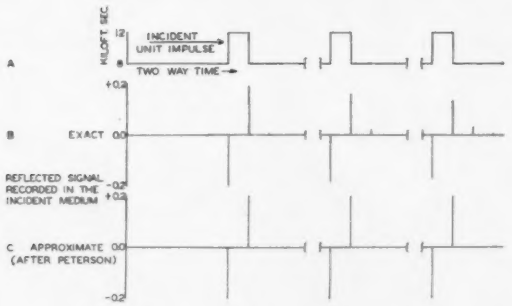

FIG. 2. Reflection of unit impulse from horizontal slabs.

The computer results agree with the analytical results to one part in a million, which is far more accurate than we actually need. For comparison, the approximate computation after Peterson is also shown. The transmission loss and filtering effect due to transmission is clearly demonstrated.

The second problem consists of three transition layers of variable velocity (Figure 3) separated vertically so that the reflections from the three layers can be obtained without interference from interformational multiples. The velocity varies linearly with increase in depth and exponentially with increase in two-way transit time. The density has been taken as constant throughout and given the value of unity.

To enter this velocity distribution into the program, it is necessary first to approximate the variable velocity zone by homogeneous layers of constant transit time. This method of approximation, as one can show from sampling theory (Goldman, 1953, Chapter 11), is adequate below a certain frequency and inade-

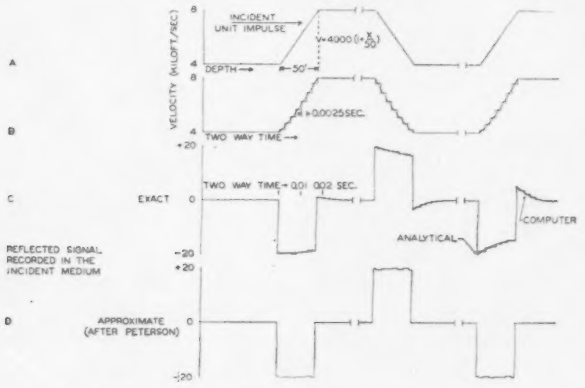

FIG. 3. Reflection of unit impulse from a transition layer.

quate above that frequency. The frequency is determined by the sampling interval, i.e., transit time. For our purposes in seismic work, a two-way transit time interval of 0.0025 sec will give an adequate approximation below 100 cps. The velocity values for these intervals were rounded to the nearest ten ft per sec prior to input. The program was written to accept data to this precision for reasons of space economy. This is justifiable since the interval velocity from the continuous velocity log is not known to this precision.

The computer results for this test problem are shown by the step-like curve (Figure 3C). The analytical results for this test problem are shown by the solid, smooth curve.

An enlargement of the deepest reflection is shown in Figure 4. The discrepancy between the computer solution and analytical solution is due to round-off error present in the input data. This round-off error is shown in the approxi-

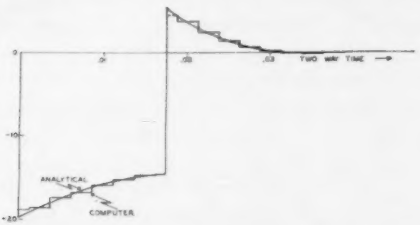

FIG. 4. Reflection of unit impulse from deepest transition layer of variable velocity shown in 3C.

mate solution, after Peterson, for the same input data (Figure 3D). In passing, it is well to call attention to the distorting effect that transmission response can produce on the reflected signal by comparing the deepest reflection with the shallowest.

The third problem, designed to literally swamp the computer with large numbers, is shown in Figure 5. An elastic half-space with a continuous linear gradient in depth (Figure 5A), or its equivalent, an exponential gradient in two-way time (Figure 5B), was used. As with the second problem, the velocity two-way time function was digitalized and the velocity in each interval rounded to the nearest ten ft per sec. The results from three of the programs are shown in Figures 5C, E, F, and G. The computer results are represented by the step-like curve while the analytical results are represented by the smooth-solid curve. The "hash" at the beginning is due to round-off error in the input. The "hash" decreases with time because the round-off error decreases percent-wise with increasing velocity. The source of error is further shown by comparison of the exact calculation with the approximate results, i.e., comparing Figure 5C with Figure 5D. Reversing the velocity distribution, i.e., using a decreasing velocity with depth function, places the "hash" at the opposite end of the particle velocity-time function.

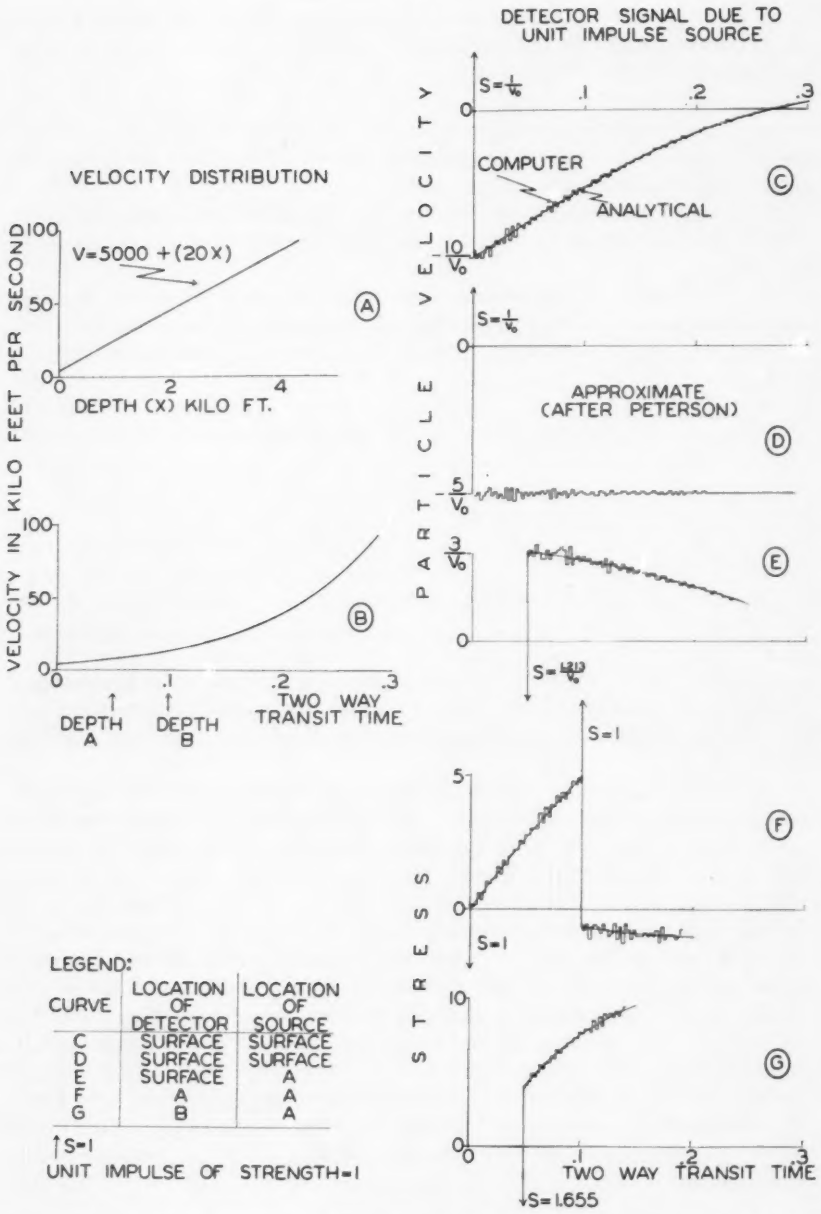

FIG. 5. Reflection of unit impulse from a half-space in which velocity is a linear function of depth.

Thus, on the basis of these three test problems, it can be concluded that the four programs are reliable, stable, and of adequate accuracy.

USE OF THE PROGRAMS

The programs described above can solve many problems of interest in reflection seismology; for example, the benefit derived from burying the detectors at a shallow depth during conventional reflection shooting can be determined, the outgoing pulse from the source can be studied by comparing the computed and recorded signal at a deep well detector, and the significance of the free surface in producing multiples can be determined. Results from studies such as these will be reported in a subsequent paper. In the remainder of this paper we will use one program, namely, the case where the source and detector are at the stress-free surface and compute synthetic seismograms. In the following presentation an attempt was made to choose examples of typical velocity distributions as given by the continuous velocity logs (CVL) for which multiples are and are not significant.

The computations to follow will be based on velocity information alone since density logs for the wells were not available. To determine the error incurred as the result of neglecting actual density data, the reasoning employed by Peterson, et al., (1955) can be followed. If density is related to a power of the velocity, i.e., $\rho = kv^n$, then the reflection coefficient using density and velocity is $(1+n)$ times the reflection coefficient based on velocity information alone providing the logarithmic approximation of the reflection coefficient is adequate. The transmission coefficient is unaffected to this degree of approximation.

The coefficients of the series of delta function pulses, equations (23) and (29), involve reflection and transmission coefficients. Thus, it would be expected that the inclusion of density would correspond approximately to an amplitude scale change of the synthetic seismogram providing that the values of k and n remained the same throughout the well. If the values vary with respect to well depth, then the scale change would vary accordingly.

The first such example where multiples can be significant in the latter half of the reflected signal is shown in Figure 6. The CVL is the top graph. Interval velocity is plotted as the ordinate using a logarithmic scale, and two-way transit time is plotted as the abscissa using a linear scale. The actual CVL has been approximated by thin homogeneous layers of constant transit time. The thickness of the layers has been chosen such that the two-way time across each layer is 0.0025 sec. As explained in the previous section, a consequence of this choice is that we are restricted in our synthetic seismograms to the frequency range less than 100 cps.

The well, represented in Figure 6, was bottomed in pre-Cambrian basement at approximately 5,000 ft. The velocity of the basement rock was assumed constant with depth below this level. The CVL covered the depth range from 600 ft to 5,000 ft. The velocity was assumed to vary linearly with depth from the datum to 600 ft. The datum, which was the stress-free surface for the multiple computa-

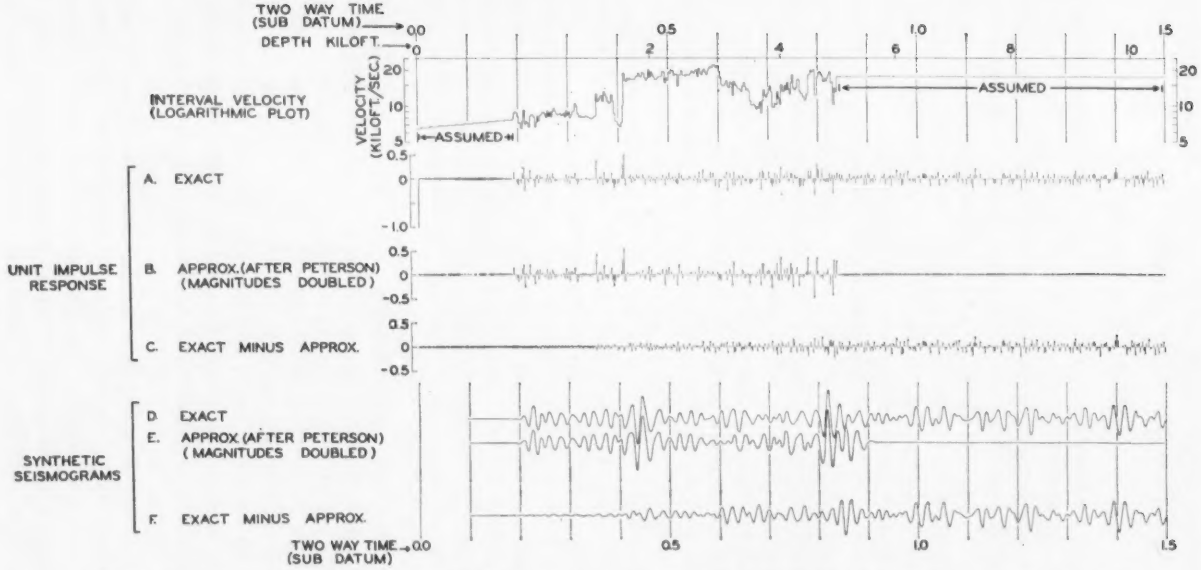

FIG. 6. Comparison of exact (plane wave case) with approximate computation of the reflected signal. Source and detector both located at surface of the multilayered elastic medium.

tion, was taken at the top of the subweathering. The reason for this choice will be discussed at the close of this section.

Figure 6A gives the results of the multiple computation for a delta-function source. The term "exact" has been used to identify this computation. The approximate computation giving only direct reflections is shown in B, and their difference is shown in C. The velocity of the source (Figure 6B), i.e., at $t=0$, has not been shown.

The convolution of Figures 6A, B, and C with the seismic pulse (shown in Figure 7) gives the Synthetic Seismograms Figures 6D, E, and F, respectively. The seismic pulse includes all filtering in the system (earth and electronic system) between the delta-function behavior of the source to the recorded seismic trace. It includes pulse broadening (an average value) due to the earth, "ghosts" of the source caused by layering above the source, and the response of the detector and of the seismic amplifier.

The Synthetic Seismograms D and E are not drastically different—both predict strong events centering approximately at 0.45 and 0.85 sec. The difference between the two seismograms is shown in F. The difference increases from zero initially to a maximum of 0.85 sec, and then remains below this maximum to the end of the seismogram. The first observed difference on the Seismograms D and E occurs at 0.6 sec, the next at the tail end of the strong event at 0.85 sec, then all signal for times greater than 0.9 sec represents multiple energy.

The synthetic seismograms are compared with a reflection record taken near the well in Figure 7. The object of this and subsequent comparisons will be to determine which synthetic seismogram more closely resembles the reflected signal on the field record. The exact agrees more closely with the reflection record for times near 0.6 and 0.85 sec. For times greater than 0.9 sec, no direct reflected energy has been included. Thus, any agreement between the exact synthetic seismogram and the reflection record identifies the recorded energy as multiple energy. From the illustration it is rather evident that all energy except perhaps that near 1.275 sec is multiple energy.

The exact synthetic seismogram predicts events that are not recorded, for example, at 1.12 sec and 1.4 sec. This is to be expected since the mathematical model is not as yet adequately realistic. The interfaces between the present model are smooth and parallel. Roughness of an interface would scatter energy and decrease its contribution to the multiples. Including dissipation in the media would also decrease the contribution of multiples to the total reflected signal. Thus, until these two effects can be included into synthesis, we can conclude that the recorded reflected signal should be somewhere between the present exact and approximate predictions.

The velocity distribution that we have chosen in Figure 6 is typical of many petroliferous areas, for example, areas where the seismic objective is to obtain reflections from small contrasts, say for instance, in the Devonian underlying a thick overburden of nearly constant velocity Mississippian, while the contrasts in

FIG. 7. Comparison of synthetic seismograms with field record.

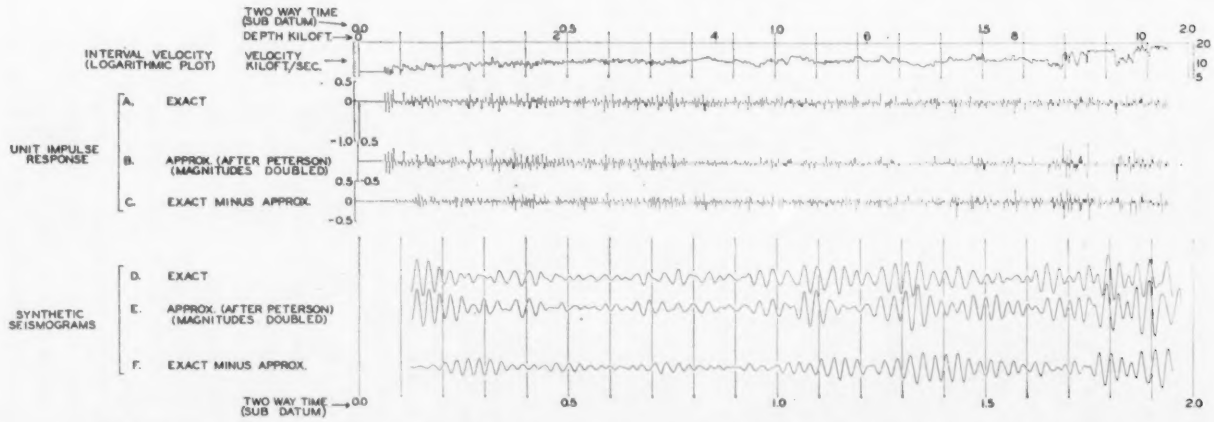

FIG. 8. Comparison of exact (plane wave case) with approximate computation of the reflected signal. Source and detector both located at the surface of the multilayered elastic medium.

the section overlying the Mississippian are large. From the demonstration given it can be deduced that multiples within the section overlying the Mississippian could mask direct reflections from the Devonian. A specific example to demonstrate this predicted result would have been advantageous; however, the data required to perform the multiple study were not readily available.

A second example wherein multiples can be important intermittently throughout the duration of the reflected signal is shown in Figure 8. The velocity distribution is characterized by a gradual increase in velocity with two-way transit time from 6,000 ft per sec to 20,000 ft per sec in a time of 2.0 sec. Super-imposed on this gradual increase are local contrasts of moderate relief. The information contained in this illustration is identical with that of Figure 6, except, of course, the seismic pulse used to obtain the synthetic seismograms is different and is shown in Figure 9.

For the velocity distribution of Figure 8, the contribution of multiples as shown by the difference between the exact and approximate computation (Figure 8F) is as large as the direct reflected signal itself. The differences are most obvious at the following times. At 1.15 sec a prominent multiple event occurs. Between 1.25 sec and 1.35 sec, multiples cause a considerable phase shift in the direct reflected signal, while between 1.35 sec and 1.45 sec the frequency of the reflected signal is lowered. Multiples depress the direct reflected signal near 1.52 sec and alter the beginning of the event at 1.62 sec. The large differences between 1.8 and 1.9 sec cause phase shifts in the direct reflected signal and alter the amplitude relationship of the reflection events at 1.9 sec to that at 1.8 sec.

The comparison of the synthetic seismograms, Figures 8D and 8E, with the reflection record taken near the well is shown in Figure 9. Again, the object is to determine which of the seismograms fits the records more closely. The event at 1.15 sec, the phasing at 1.3 sec, the frequency at 1.4 sec, and the beginning of the event at 1.6 sec, are all predicted more accurately by the exact than the approximate synthetic seismogram. The prediction for times greater than 1.7 sec is poor for both synthetic seismograms. The reason for this prediction will not be elaborated here.

A third example illustrating a velocity distribution for which the contribution of multiples is insignificant, is shown in Figure 10. The velocity increases gradually from 5,000 ft per sec to 10,000 ft per sec in a depth whose two-way transit time is 2.0 sec. Superimposed on this increase are small rather short period contrasts. The remaining information contained on this illustration is similar to that of Figures 6 and 8 with one exception, namely, Figure 10D. To obtain this result, the transmission coefficient was included in the approximate computation and the difference relative to the exact was taken. It is quite evident from comparing Figures 10C and 10D that transmission loss for the direct reflection alone does not account for the build-up with time of the difference between the exact and approximate computation as shown in Figure 10C.

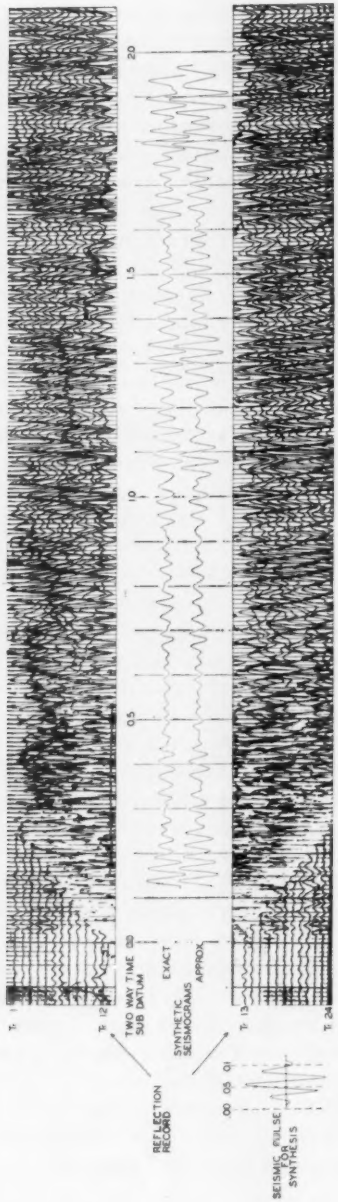

FIG. 9. Comparison of synthetic seismograms with reflection record.

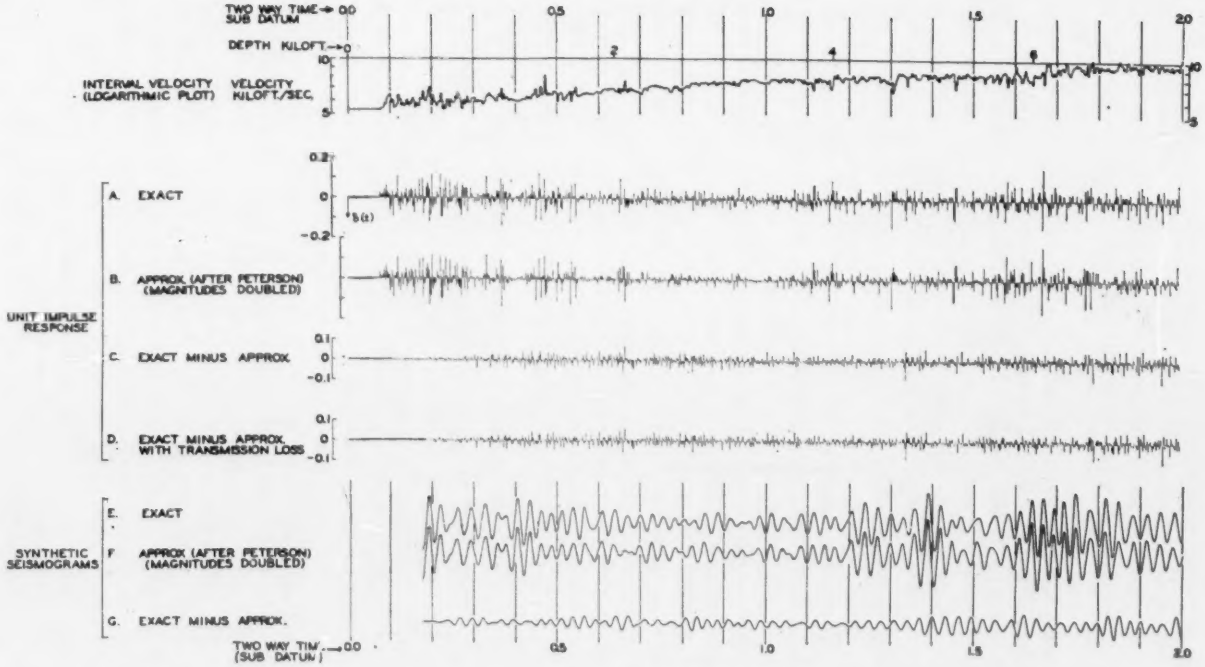

FIG. 10. Comparison of exact (plane wave case) with approximate computation of the reflected signal. Source and detector both located at the surface of the elastic medium.

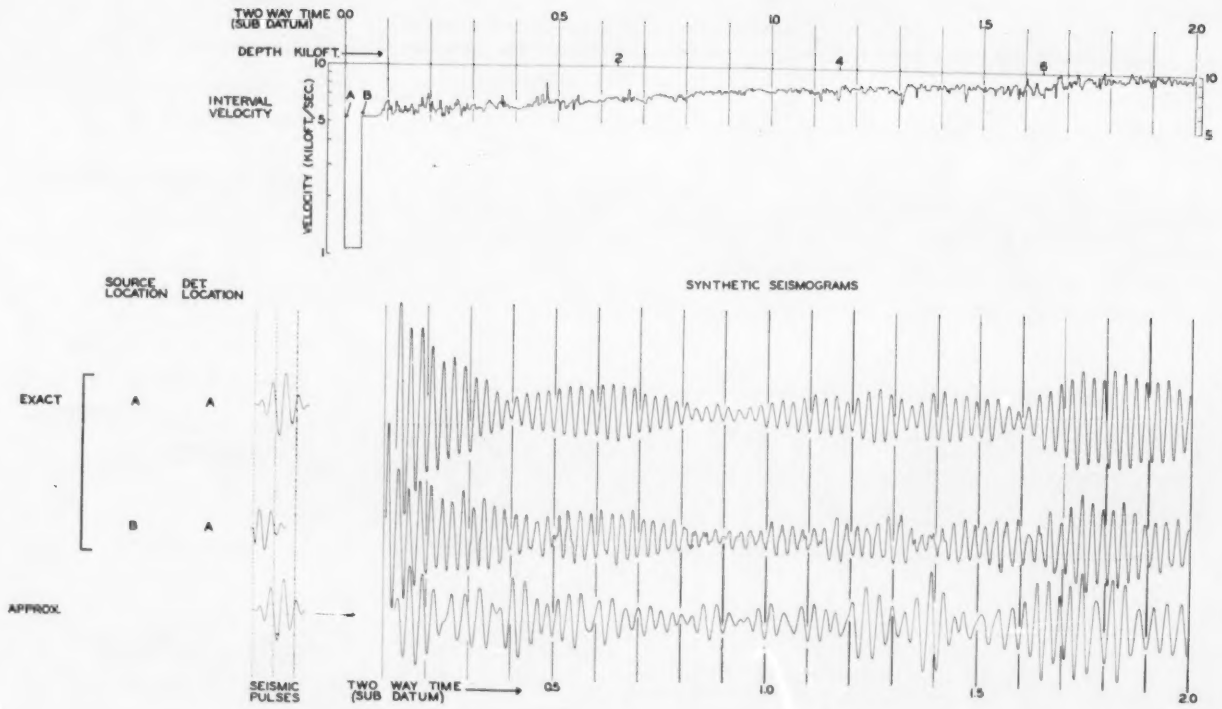

FIG. 11. Comparison of exact and approximate synthetic seismograms wi a weathering layer included.

The difference between the exact and approximate synthetic seismograms, Figure 10G, is small relative to the direct reflected signal. Multiples cause only slight distortion. This magnitude of distortion could never be observed on the field seismogram. The field seismogram taken near this well was of low quality and not reproduced here.

As a final example (Figure 11), the velocity distribution of Figure 10 will be modified by placing a low-velocity layer at the very top. The presence of this weathering layer was actually verified by uphole shooting. Three seismograms are shown. The top two include multiples, the bottom is identical to the approximate shown on Figure 10. The upper seismogram of the exact computation placed the source and detector at the stress-free surface (at point A), the lower of the two placed the source below the layer (at point B), and the detector at the upper surface (at point A).

It is quite evident that the presence of the layer considerably modifies the direct reflected signal. The approximate synthetic seismogram predicts the reflected signal recorded on the fields record much more closely than either of the exact synthetic seismograms. It was deduced, therefore, that the weathering layer in this case does not contribute multiples to the reflected signal and, therefore, should be deleted from the computation. The reason for this result is probably two fold. First, the attenuation of the weathering medium may be quite high, and second, the boundary interfaces, especially the upper surface of the weathering layer, may be quite rough. Both of these effects can reduce the multiples within the layer. At the writing of this paper, preliminary seismic model studies of this rough free surface problem confirm the above deduction.

IMPORTANCE OF THE PROGRAMS TO THE STUDY OF "RINGING" RECORDS

The exact synthetic seismograms shown in Figure 11 are of importance in understanding the cause of "ringing" records. If the top synthetic seismogram (Figure 11) were recorded through a seismic amplifier with AVC operative, the amplitude would be considerably smoothed, the degree of smoothing depending on the type and amount of AVC used. The result of this additional smoothing would yield a typical "ringing" record.

The published literature to explain "ringing" records (Burg, et al., 1951) (Liu, 1956) used as a mathematical model a single layer overlying a homogeneous half-space. Burg, et al., discussed adequately the frequency content on the "ringing" in terms of the location of the source and detector within the water layer and the thickness of the layer, but neglected to explain fully the persistence of large "ringing" amplitudes to record times of 3.0 to 4.0 sec. Liu extended the analysis of Burg, et al., to confirm not only the frequency dependance of the detector signal with depth of source and detector, but also obtained the transient amplitude response with depth, range, and time. Liu concluded that to account for amplitudes of recordable magnitudes at record times of 3.0 and 4.0 sec required ridiculous impedance contrasts between the layer and the underlying half-space.

Using as a mathematical model the multilayered half-space as we have here, the explanation of the persistence of large amplitude "ringing" to long record times is affected, the reason being that reflected energy from the multilayered medium maintains the "ringing" within the layer.

A very useful way in which to qualitatively determine the influence of the layer on the direct reflected signal is to consider the layer as a filter whose weighting function is long relative to the seismic amplifier weighting function. This weighting function is added to the outgoing pulse from the explosion if the charge is placed in or near the layer and is again added to the reflected signal returning to a detector in or near the layer. The over-all effect of the layer is then to smooth the direct reflected signal with a weighting function whose length is equivalent to the weighting function of the layer convolved upon itself. The smoothing actually produced can be seen by comparing the top and bottom synthetic seismograms, Figure 11. Knowing the cause of the "ringing," a technique for its removal becomes obvious.

CONCLUSIONS

A technique to include multiples and transmission coefficients in seismogram synthesis has been obtained by solving the boundary value problem for the multilayered half-space exactly for the plane wave case at normal incidence. The detector signal due to a unit impulse source with both source and detector at arbitrary location and with the stress-free surface of the layered half-space either present or absent was obtained in matrix form which can be easily programmed for the IBM 704, providing the transit time across all layers is made the same. The transit time has been made small relative to the seismic frequencies so that discrimination would not occur within the seismic band when continuous velocity distributions are sampled. The detector signal for a source behaving arbitrarily in time is obtained by convolution.

Each of the programs initially written for the IBM 704 accommodates 800 layers, and each computation requires 20 minutes computer time. Currently, the programs are being rewritten to accommodate 1,850 layers and to solve all problems during one machine operation.

Before using the programs to compute synthetic seismograms, they were evaluated by comparing computer and analytical solutions for simple problems. One such problem, where no input error was present, indicated the accuracy of the computer solution to be one part in one million.

Only one of the programs was used for studies reported in this paper, that being to compute synthetic seismograms for the case where the source and detector are located at the stress-free surface. Examples of velocity distributions were chosen to determine the range of significance multiples can have on the direct reflected signal and whether the multiple predictions can be verified on field seismograms.

The results of four specific examples show that for small contrasts in acoustic

impedance distributed uniformly throughout the section, multiples contribute insignificantly to the direct reflected signal. For moderate contrasts similarly distributed multiples produce discrete events, cause phase shifts in large amplitude direct reflections, and cause frequency changes in weak direct reflected signal. If the distribution is characterized by moderate to large contrasts in the shallow half of a section, and weak contrasts in the lower half, then multiples within the upper half can mask direct reflections from the lower half. If near-surface contrasts are large, then multiples within the near-surface layers can mask direct reflected signal from depth producing "ringing" or "wave training." The present analysis gives a more reasonable explanation of "ringing" records than has been given heretofore and verifies that reflected signal from depth is present on "ringing" records.

When comparing synthetic seismograms including and excluding multiples with the reflected signal on the field seismograms, it becomes evident in many cases, but not all, that the present computational techniques predict more multiple energy than is observed, which indicates that the mathematical model on which the computation is based is not as yet adequately realistic.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 130–140, 8 FIGS.

ELIMINATION OF SEISMIC GHOST REFLECTIONS BY MEANS OF A LINEAR FILTER*

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ABSTRACT

A technique is described for elimination of ghost reflections on magnetically recorded seismograph records by means of a linear filter. The application of this filter does not alter the character of primary reflections although eliminating the ghost reflections. The principal assumption made in the development of the technique is that the effect of AGC in altering the amplitude ratio of primary and ghost reflections is uniform for all record time.

A realization of the required filter is given and a measurement technique is outlined for detecting the existence of ghost reflections based on the autocorrelation function of the seismograph trace.

The existence of a large velocity discontinuity above a seismic shot has long been recognized as the source of "ghost" reflections appearing on the seismogram In such instances, the downgoing wavefront set up by the shot is characterized by energy moving directly downward from the shotpoint followed in space and time by energy reflected from the overlying discontinuity. When detected, this downgoing wavefront appears as two wavelets displaced in time by approximately twice the travel time from the shot to the discontinuity and with possible differences in shape. Any difference in shape may be attributed to tuning effects of the ground between the shot and the discontinuity and the sphericity of the incident wavefront at the discontinuity. These relationships are illustrated in Figure 1.

The wavelet associated with the incident component of the downgoing wavefront will be designated as $b(t)$, a time function having a LaPlace transform $B(s)$ (Gardner and Barnes, 1942; Goldman, 1955). The wavelet associated with the reflected component of the downgoing wavefront will have the LaPlace transform $\mathfrak{a}H(s)B(s)e^{-s\tau}$ where $\mathfrak{a}$ is the reflection coefficient at the overlying boundary, $H(s)$ represents the tuning effects of the two passes through the strata between the shotpoint and the boundary, and $e^{-s\tau}$ is the LaPlace time delay operator having τ seconds delay (Gardner and Barnes, 1942; Goldman, 1955). The symbol τ represents the time lag of the ghost wavefront. Any pure loss of the overlying strata will be included in the factor $\mathfrak{a}$. Having made these definitions, the LaPlace transform of the total wavelet representing the downgoing wavefront is,

$$B(s) - \mathfrak{a}H(s)B(s)e^{-s\tau}. \qquad \text{(a)}$$

When an impulse is presumed to excite the subsurface layering, the response wavelet received by the surface detector will be denoted by the time function

* Presented at Twelfth Annual Midwestern Meeting, El Paso, Texas, April 28, 1959. Manuscript received by the Editor July 14, 1959.

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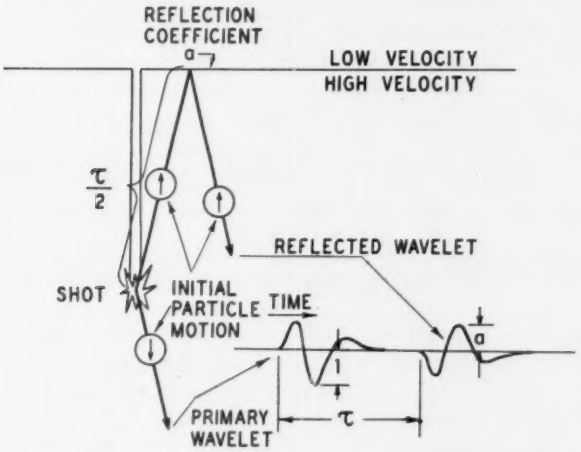

FIG. 1. Illustration of the relation between primary and ghost wavefronts generated by the seismic shot.

$r(t)$ having LaPlace transform $R(s)$. Therefore, for the excitation represented by expression (a), the surface response will be,

$$R(s)\left[B(s) - \alpha H(s)B(s)e^{-s\tau}\right]. \tag{b}$$

The response desired at the surface is that generated by only the incident wavefront set up by the shot. This component of the surface response is given by the LaPlace expression,

$$R(s)B(s). \tag{c}$$

Now the filter required to eliminate ghost reflections may be defined as one that converts the total response at the surface to the primary reflections alone. This conversion process will be specified as the operation of linear filtering (Robinson, 1954). This filter, designated $F(s)$, may be mathematically described as,

$$F(s)R(s)\left[B(s) - \alpha H(s)B(s)e^{-s\tau}\right] = R(s)B(s),$$

$$F(s) = \frac{R(s)B(s)}{R(s)\left[B(s) - \alpha H(s)B(s)e^{-s\tau}\right]},$$

$$F(s) = \frac{1}{1 - \alpha H(s)e^{-s\tau}}. \tag{1}$$

Realization of this filter is made quite easy by observation of the similarity between the transfer function as given by (1), and the general expression for the

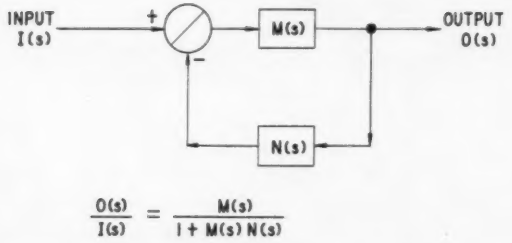

FIG. 2. Generalized single loop feedback system employing negative feedback.

transfer function of a system with feedback. The generalized single-loop feedback system and its transfer function are shown in Figure 2. The numerator of the transfer function represents the transfer function of the forward loop and the second term of the denominator represents the product of all transfer functions around the loop. By analogy, the required filter, when represented in the configuration of a single-loop feedback system, will have a forward loop transfer function of unity and a transfer function around the loop of $\alpha H(s)e^{-s\tau}$. The resulting feedback system is indicated in Figure 3.

This filter converts a primary reflection plus ghost reflection at the input into a primary reflection only at the output. Likewise a series of primary reflections plus their respective ghosts is transformed into the primary reflection series only. This action is more easily seen by considering a single primary-ghost wavelet sequence. Upon entering the filter, a primary wavelet appears at the output with no delay and simultaneously is stored in the delay unit. As its ghost wavelet enters the filter τ seconds later, the stored primary wavelet is transformed by $H(s)$ to have the same shape as the ghost wavelet, and thus cancels the ghost wavelet at the output of the filter.

It is important to point out here that only the portions of the seismic record subject to the ghosting conditions should be admitted to the input of the ghost elimination filter. Any event such as first-break wavelets, which have no ghost

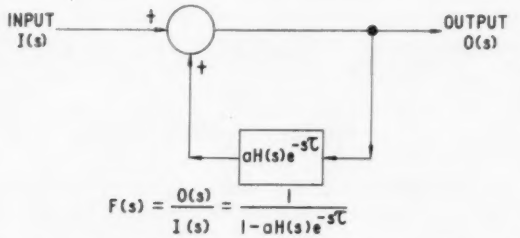

FIG. 3. Feedback system which realizes the transfer function of equation (1). (Note that feedback must be positive).

wavelet following, will be duplicated many times at the output of the filter with obviously undesirable results. This is demonstrated by expanding the transfer function $F(s)$ into an infinite series:

$$F(s) = 1 + \alpha H(s)e^{-s\tau} + \alpha^2 H^2(s)e^{-2s\tau} + \alpha^3 H^3(s)e^{-3s\tau} + \cdots \quad (2)$$

When the earth tuning, $H(s)$, is negligible, this series reduces to,

$$F(s) = 1 + \alpha e^{-s\tau} + \alpha^2 e^{-2s\tau} + \alpha^3 e^{-3s\tau} + \cdots \quad (3)$$

This is the response of the ghost-elimination filter to an impulse input, and consists of a series of impulses decaying in amplitude at the rate α per time τ, and spaced τ seconds apart. Likewise, if any single event enters the filter, the output is an infinite repetition of the event every τ seconds and decaying exponentially in amplitude. This problem is usually resolved by electronically eliminating early arrivals on the record before passing the signals through the filter.

The "earth" filter, represented by $H(s)$, will of course, take on many forms depending upon the nature of the strata overlying the shot. If the base of the weathering is the ghost-producing boundary and there is no inhomogeniety between the shot and the weathering, there may be no need for the earth filter at all. If the surface is the ghost-producing boundary and [illegible] layering is present between the shot and the surface, a relatively simple filter that emphasizes the low frequencies with about a six db per octave attenuation will suffice. The filter should be phase corrected and have its three db attenuation point at a frequency appropriate for the ground characteristic. A large degree of inhomogeneity or complicated layering between the shot and the ghosting boundary generally washes out the ghost energy sufficiently that ghosts are not the primary problem. In the majority of cases where elimination of ghost reflections is required there is no need for the earth filter.

The obvious problem in setting up the ghost-elimination filter is to determine the parameters α, $H(s)$ (if required), and τ. If field procedure permits, these may be obtained from a down-hole seismometer recording with the seismometer placed below the shot level. Aside from the problems associated with obtaining this trace, it often happens that magnetically recorded data is already in hand and the field work completed before the problem of ghost reflections is recognized. Consequently an alternate method of determining the ghost parameters is desirable. Examination of the autocorrelation function (Robinson, 1954) of the seismic record will indicate that the parameters α and τ may be determined, although accurate definition of $H(s)$ from the autocorrelation function is seldom possible, as will be shown later.

The truncated autocorrelation function of a seismic trace measured over the time interval $t_2 - t_1$ is defined as,

$$A(\sigma) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} X(t)X(\sigma + t)dt. \quad (4)$$

The interval t_2-t_1 will be chosen so that only events subject to the ghosting conditions are included. When ghosts are present on the trace, the function $X(t)$ may be expressed as

$$X(t) = Y(t) - \alpha Y(t-\tau), \tag{5}$$

if the effects of earth tuning are neglected. In this notation, $Y(t)$ represents the primary reflection series.

Substituting expression (5) into (4) yields,

$$A_{p+g}(\sigma) = \frac{1}{t_2-t_1}\int_{t_1}^{t_2}[Y(t) - \alpha Y(t-\tau)][Y(\sigma+t) - \alpha Y(\sigma+t-\tau)]dt,$$

and,

$$A_{p+g}(\sigma) = \frac{1}{t_2-t_1}\Bigg[\int_{t_1}^{t_2} Y(t)Y(\sigma+t) + \alpha^2\int_{t_1}^{t_2} Y(t-\tau)Y(\sigma+t-\tau)dt$$
$$- \alpha\int_{t_1}^{t_2} Y(t)Y(\sigma+t-\tau)dt - \alpha\int_{t_1}^{t_2} Y(\sigma+t)Y(t-\tau)dt\Bigg]. \tag{6}$$

The autocorrelation function of the primary reflection series alone is,

$$A_p(\sigma) = \frac{1}{t_2-t_1}\int_{t_1}^{t_2} Y(t)Y(\sigma+t)dt. \tag{7}$$

Comparison of (6) and (7) gives a relation between the autocorrelation function of primary plus ghost reflections to the autocorrelation function of primary reflections alone:

$$A_{p+g}(\sigma) = (1+\alpha^2)A_p(\sigma) - \alpha A_p(\sigma+\tau) - \alpha A_p(\sigma-\tau). \tag{8}$$

Thus, the autocorrelation function of a trace having primary and ghost reflections is composed of the sum of three autocorrelation functions of the primary reflection series. These three autocorrelation "wavelets" are separated in time by τ seconds, and the ratio of the amplitude of the center wavelet to that of the adjacent two wavelets is $(\alpha^2+1)/\alpha$. Figure 4 illustrates these features. Two of these autocorrelation wavelets exist only because of the ghosting conditions. That is, if the quantity α in (8) were reduced to zero, which would be the case when no ghost is present, only one autocorrelation wavelet would exist. Therefore, the presence of ghost reflections on a record is indicated by the three-wavelet appearance of the autocorrelation function. When analyzing the autocorrelation function for ghost parameters, it is convenient to compute α from the amplitude of the ghost-indicating autocorrelation wavelet normalized to the autocorrelation value at zero stepout. This amplitude, denoted by m, is,

$$m = \frac{\alpha}{\alpha^2+1}. \tag{9}$$

$$A_{p+g}[\sigma] = [1+\alpha^2]A_p[\sigma] - \alpha A_p[\sigma+\tau] - \alpha A_p[\sigma+\tau]$$

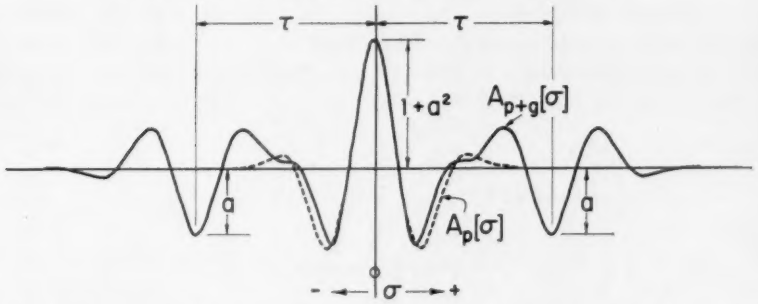

FIG. 4. Illustration of the relation between the autocorrelation function of a seismic trace with ghost reflections and the autocorrelation function of the same trace with only primary reflections. (Note the "tails" produced by the ghost reflections.)

Solution for α may be made in terms of m.

$$\alpha = \frac{1}{2m} - \sqrt{\frac{1}{4m^2} - 1}. \tag{10}$$

The relation (10) is plotted in Figure 5. The maximum value of m is 0.5 when the reflection coefficient at the ghosting boundary is unity.

It is possible in theory to determine the earth tuning from the characteristics of the autocorrelation function. If there is significant tuning of the earth, it is recognized in the autocorrelation function by a difference in character between the center wavelet shape and the adjacent wavelet shapes at stepout, $\pm\tau$. By relating the spectra of these two wavelet components of the autocorrelation function, the amplitude and phase characteristic of the earth filtering may be determined. In practice this technique usually fails because the detail characteristic of the two wavelet shapes is lost in the "noise" of the autocorrelation function which results from a finite measurement interval, and thus an imperfect statistical sampling.

The ability of the autocorrelation function to portray the character of the basic seismic wavelet generating the trace is directly related to the degree of randomness of the time of arrival and amplitude of the myriad of these basic wavelets. The autocorrelation function of a stationary random series of identically shaped wavelets is the autocorrelation function of the wavelet (Robinson, 1954). Experience indicates that as little as 0.5 sec samples of a seismic trace reasonably well approximates these conditions of randomness. The large number of appreciable reflection coefficients obtained by uniformly sampling the interval velocity log lends support to this viewpoint.

The ghost delay time (τ) is readily measured from the autocorrelation function. Comparison of this time to twice the uphole time as indicated by the shothole seismometer always shows the uphole time to be less than half the ghost time. A possible explanation for this discrepancy lies in the method of picking the uphole time. It is customary to make the pick on first-break energy which gives the travel time for high frequency components. The autocorrelation measure-

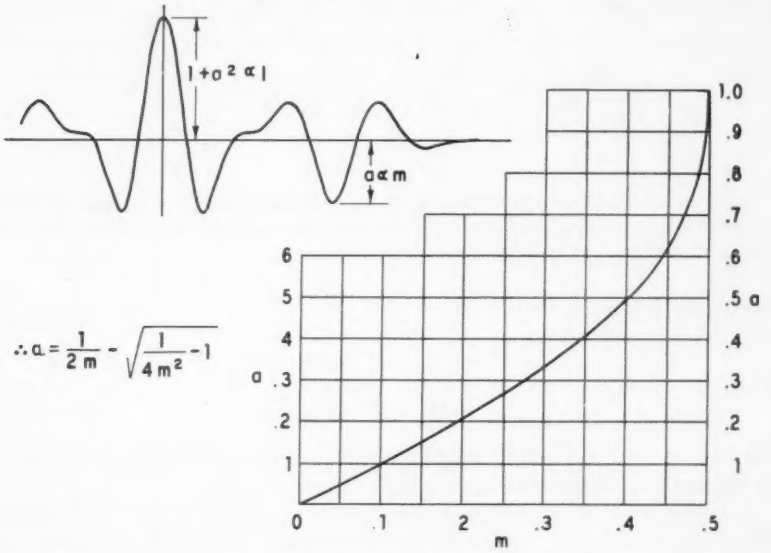

FIG. 5. A plot of the relation between reflection coefficient α and the the ratio m obtained from the autocorrelation function.

ment indicates a ghost travel time that applies to the frequency of major content on the record. If there is any dispersion in the surface layering these two travel times will be different.

In Figure 6 the significant part of a field record is shown in which ghost reflections are prevalent. With only the record to judge by, it is difficult to be certain of the existence of ghosts. The autocorrelation function of each trace of this record was measured over a time interval of approximately 3 sec including the 800 millisec shown. These are shown in Figure 7. For better averaging of the extraneous "noise" of the autocorrelation functions, the sum of the twelve autocorrelation functions was used to determine the ghost parameters. In this case the value of τ is 0.109 sec and the value of m is 0.47. Referring to Figure 5, α is determined to be approximately 0.7. No earth tuning is apparent since the component wavelet shapes are very nearly the same.

After elimination of the ghost reflections by means of the filter, the record

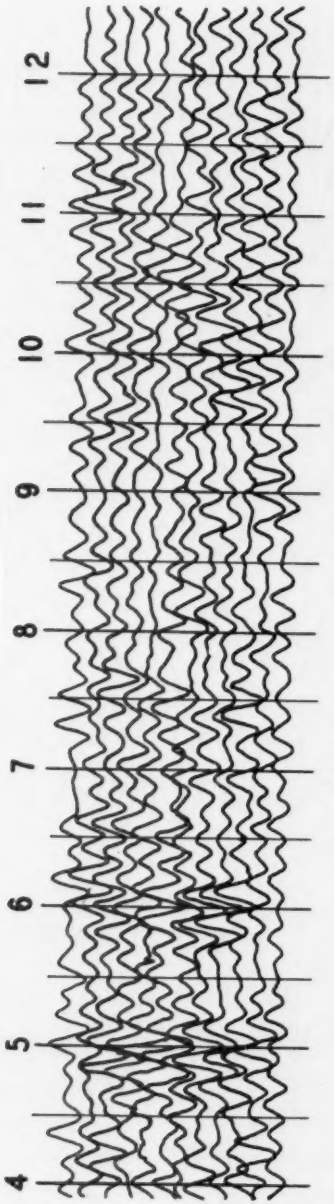

FIG. 6. A portion of a field record containing ghost reflections.

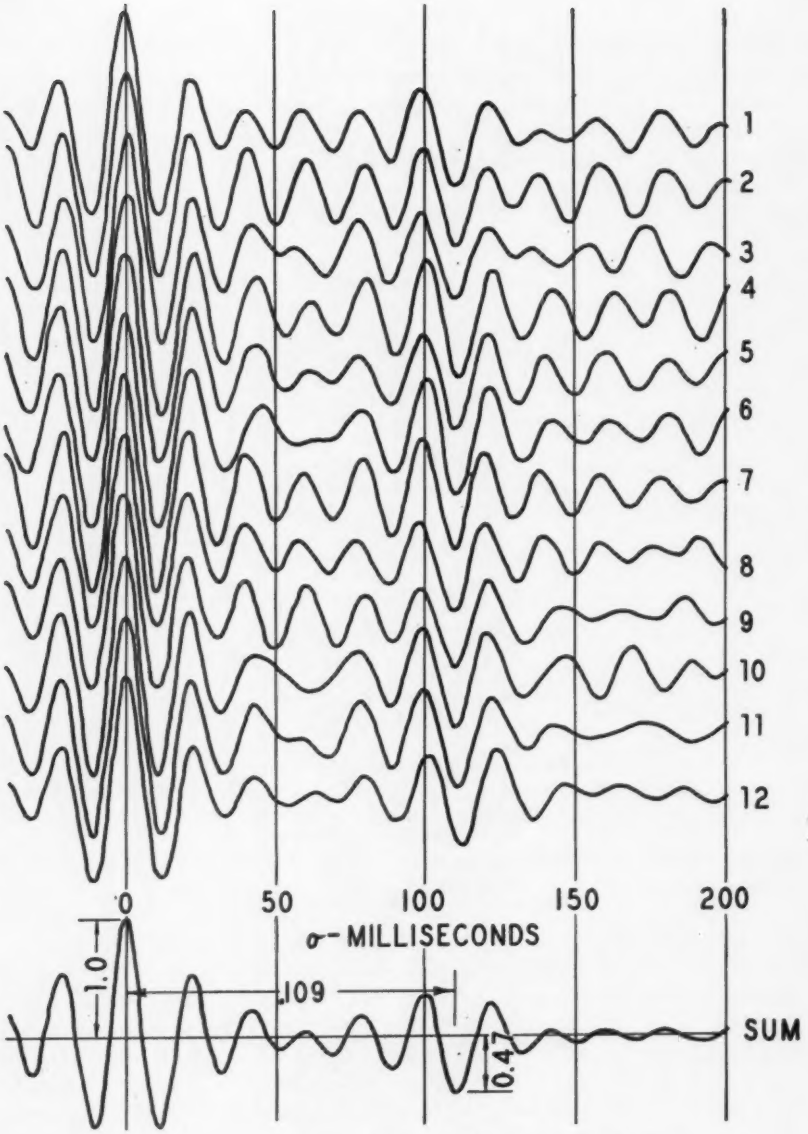

FIG. 7. The measured autocorrelation functions of the record of figure 6.

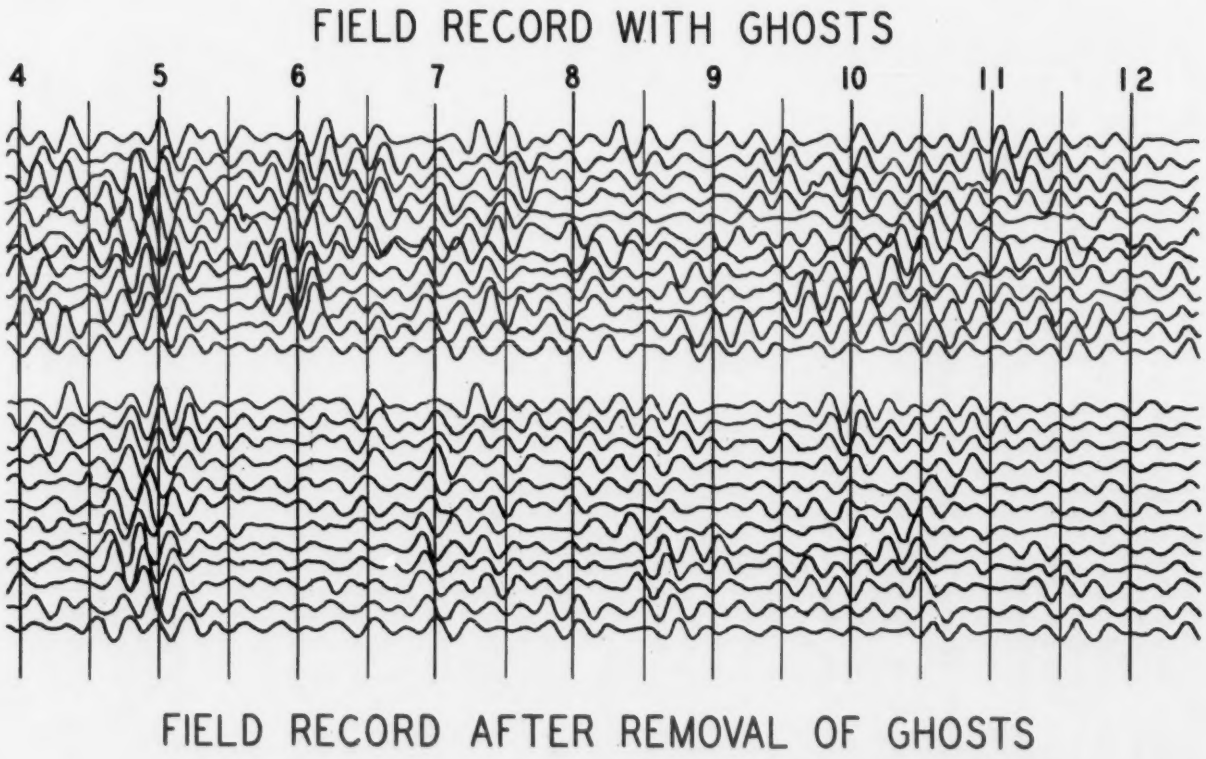

FIG. 8. A comparison of the field record of figure 6 before and after elimination of the ghost reflections by means of an appropriate filter.

appearance is somewhat different as indicated in Figure 8. Note the primary reflection at 0.860 sec that had been obscured by a ghost arrival.

The effects of AGC have been ignored in this treatment although it is possible for rapidly changing gain to alter the amplitude ratio between a primary and its ghost along the record. A slow AGC usually minimizes this problem so that it is negligible. Very rapid AGC should be avoided if ghost elimination is to be attempted in this manner.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 141–167, 34 FIGS.

OUTLINING OF SALT MASSES BY REFRACTION METHODS*

A. W. MUSGRAVE,† W. C. WOOLLEY,† AND HELEN GRAY†

ABSTRACT

Short surface-to-surface refraction lines define the top of a shallow salt dome previously located by reflection methods. A map is made from the results of a number of longer refraction lines radiating from the center of the dome. The increased accuracy of this system is primarily dependent upon the accurate determination of velocities and distances.

Flank wells are used for further refraction shooting which yield more accurate velocity information and more detailed salt profiling. A map from this integrated information permits exploitation at a minimum risk, even though every location is essentially a wildcat.

INTRODUCTION

Earlier papers by McCollum and LaRue (1931) and Gardner (1949) have described various methods for delineating salt domes. The method described here utilizes many of the ideas developed in those papers as well as new techniques to give an integrated salt mapping program. The salt mass used is a hypothetical example encompassing many of the special features that the authors have encountered while interpreting numerous salt features. The example includes special problems inherent to water covered areas.

This paper develops methods for mapping salt masses consisting of five steps, three in phase one, and two in phase two.

In phase one, called the Exploration Phase, the first step is to locate salt masses by reconnaissance shooting. The second step is to shoot short refraction lines to determine the depth to, and the location of the top of the salt. In the third step, longer and more detailed surface-to-surface refraction lines are shot, and locations for at least three flank wells are made on the map drawn from these profiles.

In phase two, called the Exploitation Phase, the first step is to shoot salt proximity profiles to determine the distance between the flank wells and the salt-sediment interface. For the second step, salt profiles of the side opposite the flank well are obtained which give more detail and yield greater depth control.

EXPLORATION

Reflection

Salt masses are originally located by reconnaissance geophysical methods. The reflection seismic method is best for this purpose. Figure 1 shows the salt mapped by an absence or cutout of reflections. Even though a detailed reflection

* Paper read at the 28th Annual Meeting of the Society at San Antonio, October 14, 1958, manuscript received by the Editor, February 19, 1959.

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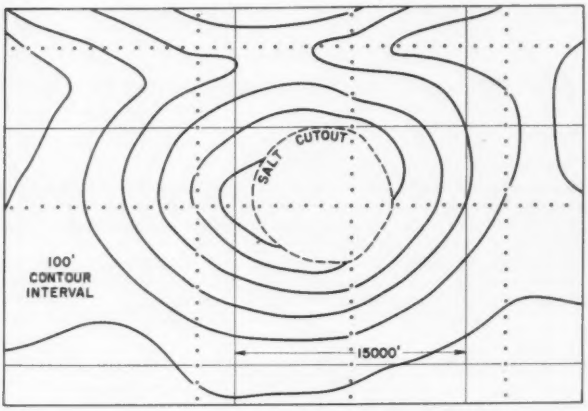


FIG. 1. Salt cutout on reconnaissance reflection map.

program could be used, this negative indication would still not be as accurate as the map obtained from the refraction seismic method.

Refraction

In addition to good instrumentation and accurate time measurement, two other quantities are necessary for salt dome refraction work. They are: (1), the

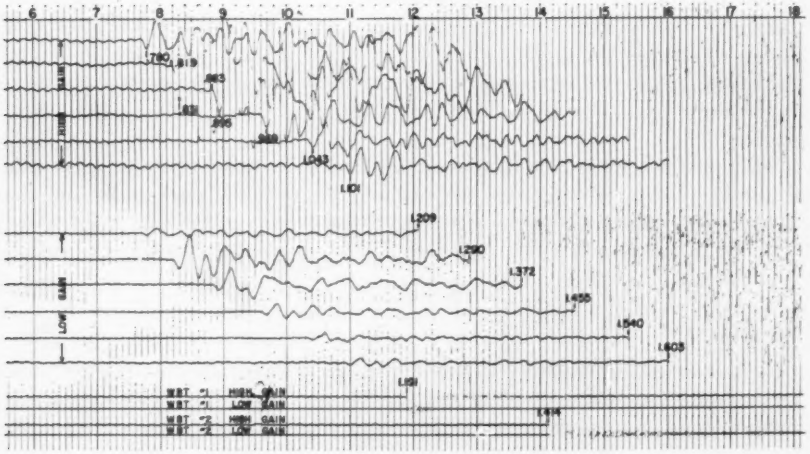


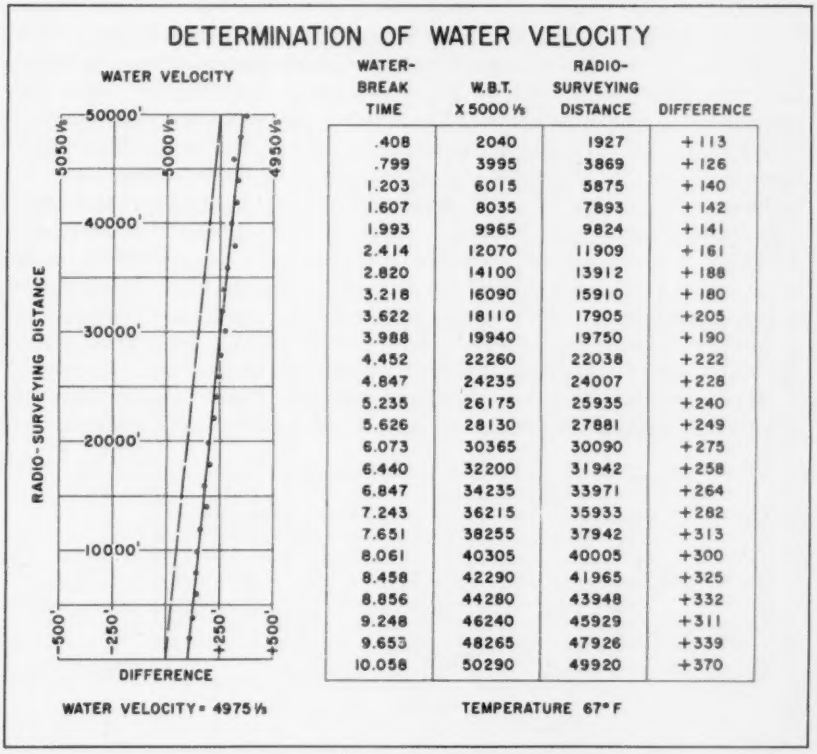
FIG. 2. Seismograph record showing refractions (first breaks and first troughs) and water breaks on each trace recorded with flat amplifiers, also water break phones 100 ft off close end of cable and in center of cable recorded using high-pass filters.

distance between the shot and phone and, (2) the velocities of the salt and the sediments outside the salt.

Distance

A high degree of surveying accuracy is vital in refraction work. Offshore this presents special problems which have been solved by recording and using water breaks (Figure 2). Flat response amplifiers are used in recording two gains. The high gain shows first trough counts and two first-break counts. The low gain shows the water breaks for each trace. Water-break phones near one end and in the center of the cable are recorded at two gains on a high-pass filter.

Radio surveying is used dually for guiding the boats to the right location for shooting and recording, and for calibrating the water velocity. Distances are ob-



WATER-BREAK TIME	W.B.T. X 5000 ft/s	RADIO-SURVEYING DISTANCE	DIFFERENCE
.408	2040	1927	+113
.799	3995	3869	+126
1.203	6015	5875	+140
1.607	8035	7893	+142
1.993	9965	9824	+141
2.414	12070	11909	+161
2.820	14100	13912	+188
3.218	16090	15910	+180
3.622	18110	17905	+205
3.988	19940	19750	+190
4.452	22260	22038	+222
4.847	24235	24007	+228
5.235	26175	25935	+240
5.626	28130	27881	+249
6.073	30365	30090	+275
6.440	32200	31942	+258
6.847	34235	33971	+264
7.243	36215	35933	+282
7.651	38255	37942	+313
8.061	40305	40005	+300
8.458	42290	41965	+325
8.856	44280	43948	+332
9.248	46240	45929	+311
9.653	48265	47926	+339
10.058	50290	49920	+370

FIG. 3. Observed data for determining water velocity. Also plot of difference between radio-surveying distance and water-break time×5,000 ft/sec versus radio-surveying distance. Water velocity, 4,975 ft/sec, is read as the 50,000 ft intercept of the dashed line which is parallel to the solid line and through the origin.

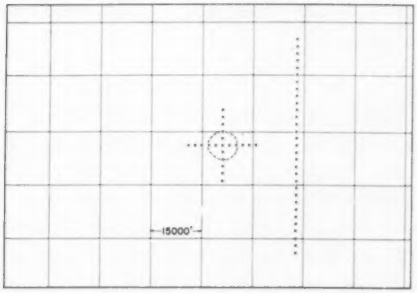


FIG. 4. Layout of surface-to-surface normal refraction line for sedimentary velocity determination.

tained by multiplying the water-break times by the water velocity, which is determined as follows. When lines are being shot, both boats take readings from a radio-surveying system which record the position of each shotpoint, and a position relative to each cable location. The data from the radio-surveying system are converted by an electronic computer into distance (Figure 3). Water-break times are picked for all phones and these times multiplied by 5,000 ft/sec. The radio-surveying distances for each phone are subtracted from the values obtained from water breaks. These differences are plotted versus their respective radio-surveying distances. A sample is shown using a scale of 1 unit = 250 ft for the differences and 1 unit = 5,000 ft for the radio-surveying distances. The water velocity is read as the 50,000 ft intercept of the dashed line through the origin and parallel to the line through the data. Each unit equals 25 ft/sec with the vertical line being 5,000 ft/sec. Thus, the water velocity in this case is 4,975 ft/sec.

If possible, periodic readings of water temperature should be taken during the shooting. Approximate velocities may be obtained from these temperatures, using

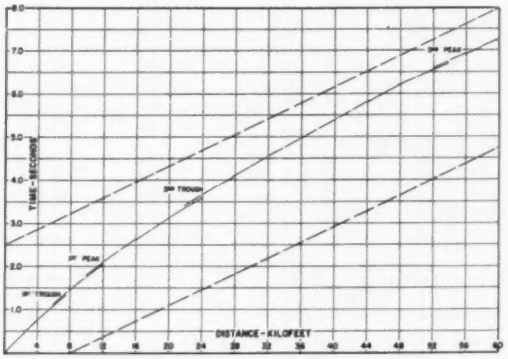


FIG. 5. Time-distance plot of normal line.

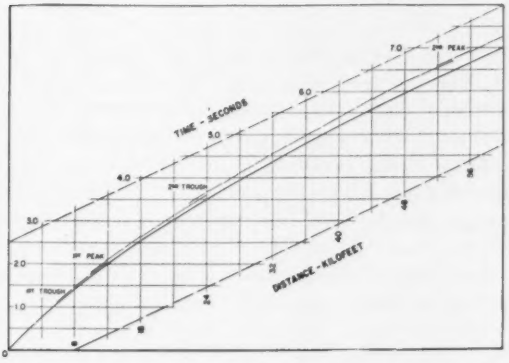


FIG. 6 Adjusted and projected continuous first-break line derived by backoff from later events in the same wavelet (shown on diagonal paper).

the tables in the Hydrographic Manual (Adams, 1942), and government salinity tables. In the Louisiana Gulf, a salinity of 35 parts per thousand is typical, except near river outlets. The velocity values from the tables are used as an added check, particularly when shooting has taken place before and after a storm. At these times, temperatures, and consequently velocities, may vary markedly in a few hours.

Distances obtained by water-break times and water velocity are true radial distances from charge to phones. This method eliminates possible errors due to drifting of charge or phone cable.

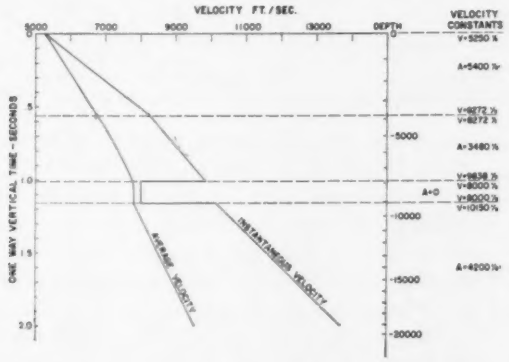


FIG. 7. Determination of velocity constants for a four-layer problem. The time versus velocity plot yields straight-line segments for the instantaneous velocity and slightly curved lines for the average velocity plot. The instantaneous velocity at the top and bottom of each layer is given along with the acceleration (which is the slope of the instantaneous velocity).

Velocity

The velocity of the salt is usually quite uniform and about 15,000 ft/sec. However, it has been found to vary as much as four percent from this value.

Accurate control of sedimentary velocity is necessary since velocity varies with depth and since there is usually a large ratio of sedimentary travel to salt travel. A vertical wavefront chart may be calculated from (1), the best vertical velocity information available in the area, (2) a horizontal velocity survey as described later, which may be fitted by a mathematical relationship and extended in depth and (3) a surface-to-surface refraction line, sometimes called a normal line. Since the third method can be shot at the time of the reconnaissance refraction lines, it will be described in some detail (Figure 4).

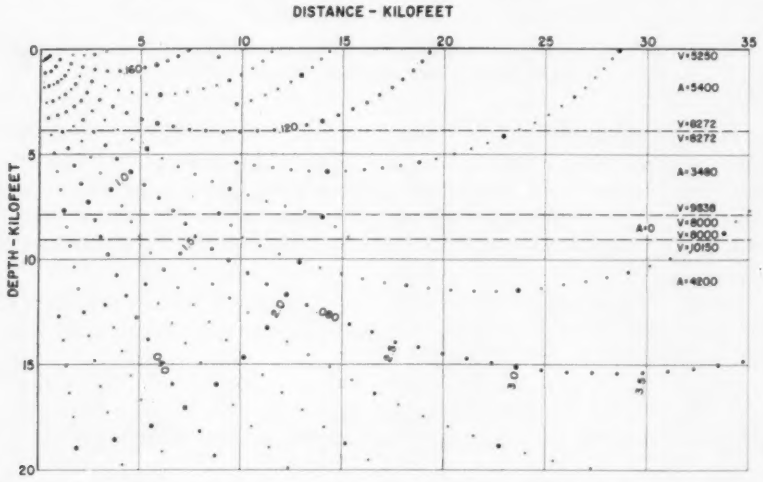


FIG. 8. Plot of information from electronic computer showing intersection of wavefronts and raypaths

A surface-to-surface refraction line, shown east of the dome, is shot in a region of normal sedimentary section in the area near the dome. A plot, Figure 5, is made of first-break times versus distance. For lines of this length, 10 ft or more to scale, diagonal paper (such as shown between the dashed lines in Figure 5) may be made in order to maintain plotting accuracy within a reasonable space. As first breaks become too weak to pick, first peaks or troughs are used. This is justified on the basis that the phase velocity in the first wavelet remains nearly constant. Lines are drawn through this data with the slopes changing where necessary to obtain a best fit. A continuous first-break line (solid line) is derived using these slopes (Figure 6). This line should fit the first breaks as well as possible and should parallel the slopes of later events, thus being representative of the first breaks had they been obtained.

From this "break line," a set of constants (Figure 7) is derived describing the velocity vertically by use of the cycloidal raypath method (Musgrave, 1952). The constants involve an initial velocity, an acceleration, and a final velocity or depth for each layer. On the velocity versus vertical time plot, the instantaneous velocity is represented by straight line segments. The velocity in each layer may either vary linearly with time or be constant. However, the average velocity lines after the first layer are slightly curved. With these constants a wavefront chart (Figure 8) is computed and plotted by an electronic computer. Up to 40 layers

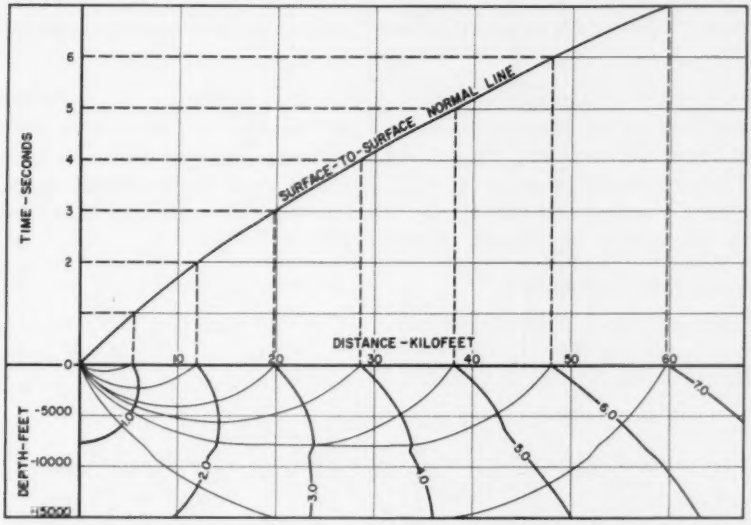


FIG. 9. Plot showing the correspondence between the observed surface-to-surface refraction first breaks and the mathematical chart.

can be used in the program which we have developed for the computer. The wavefront chart (Figure 9) will fit the observed line at the surface. Although this is not a unique solution, it should be sufficiently accurate and conforms to the best information available. The method for obtaining the constants for a chart is rather involved and a detailed explanation is beyond the scope of this paper.

A raypath is an imaginary line which is normal to all wavefronts. It is important because it is, one, the basis of this type of wavefront chart, and two, necessary for surface-to-surface refraction plotting.

The angle of emergence (Figure 10) of the raypath is obtained by solving the right triangle for sin α_0. This in turn may be solved for ΔT by rearranging the equation. The parameter p of the raypath is equivalent to the sine of the angle

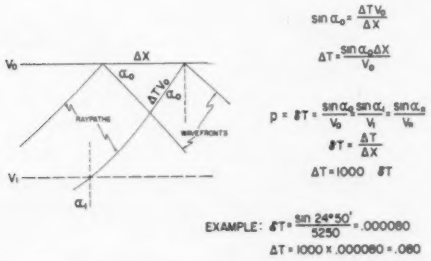

$\sin\alpha_0 = \frac{\Delta T V_0}{\Delta X}$
$\Delta T = \frac{\sin\alpha_0 \Delta X}{V_0}$
$p = \delta T = \frac{\sin\alpha_0}{V_0} = \frac{\sin\alpha_1}{V_1} = \frac{\sin\alpha_n}{V_n}$
$\delta T = \frac{\Delta T}{\Delta X}$
$\Delta T = 1000 \ \delta T$
EXAMPLE: $\delta T = \frac{\sin 24°50'}{5250} = .000080$
$\Delta T = 1000 \times .000080 = .080$
V_0
ΔX
α_0
$\Delta T V_0$
RAYPATHS
WAVEFRONTS
V_1
α_1

FIG. 10. Diagram defining the raypath parameter, p, and stating the relationship between δT, ΔT, and the emergent angle α.

divided by the instantaneous velocity. According to Snell's law, this is the same for any layer. From these relations δT is the difference in time on a wavefront chart per unit of horizontal distance. ΔT is normally used where ΔX equals 1,000 ft. The raypaths are shown in Figure 11. Points of equal time along each raypath are joined to form wavefronts (Figure 12). This wavefront chart should represent all the information available on the sedimentary velocity.

Reconnaissance Refraction

The next step in developing a picture of the salt mass is to shoot two short surface-to-surface refraction lines (Figure 13), crossing each other at right angles. Their intersection should be as near the center of the dome as possible from the

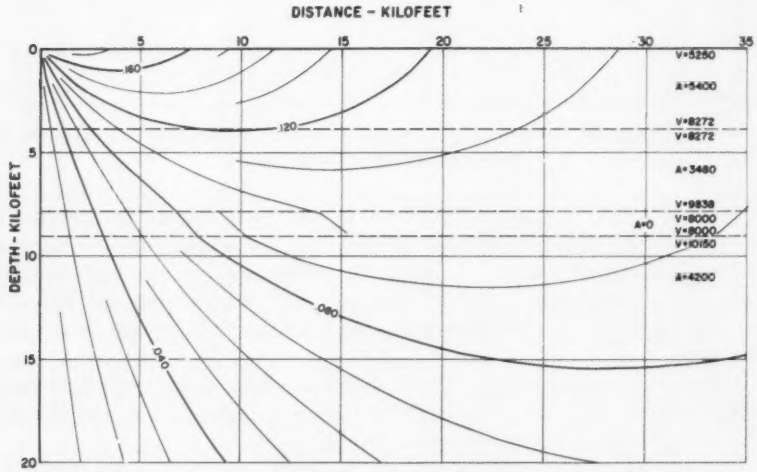


FIG. 11. Chart with raypaths only. These are labeled in terms of change of time per 1,000 ft of horizontal distance.

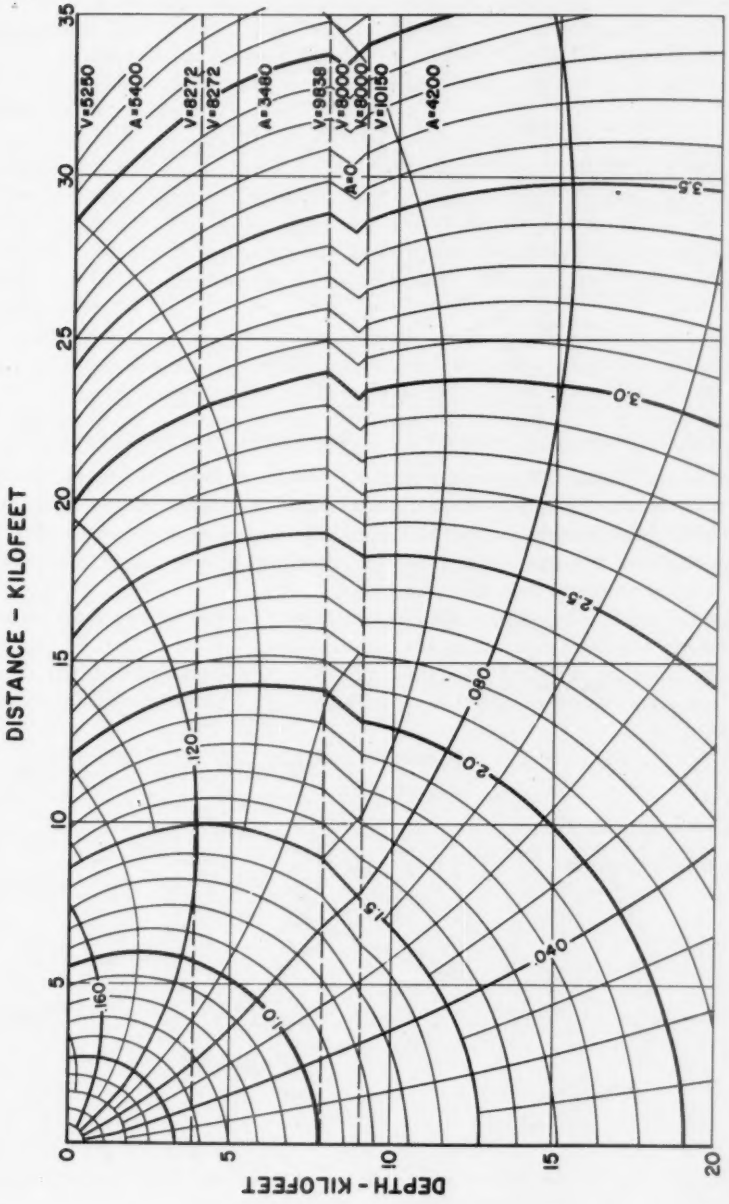


FIG. 12. Wavefront chart showing both wavefronts and raypaths—note the loss of the raypath whose $\Delta T = 0.100$.

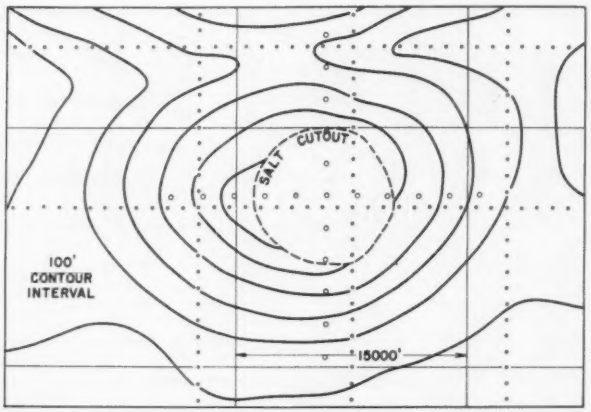


FIG. 13. Location of the two short-refraction lines (large circles) on reflection map.

information available. The purpose of these lines is to locate the center of the dome more accurately and to determine the approximate depth of the top of the dome. For this shooting, two boats are used. The recording boat tows a 2,000 ft long multiphone floating cable, while the shooting boat occupies shotpoints 2,000 ft apart along the line of survey.

The derived first-break lines are plotted (Figure 14) for the two short-refraction lines in the same manner as the normal line described earlier. For future plotting, times are recorded from these lines for each shotpoint distance. Also, times and distances are recorded for changes of slope which occur between shotpoints.

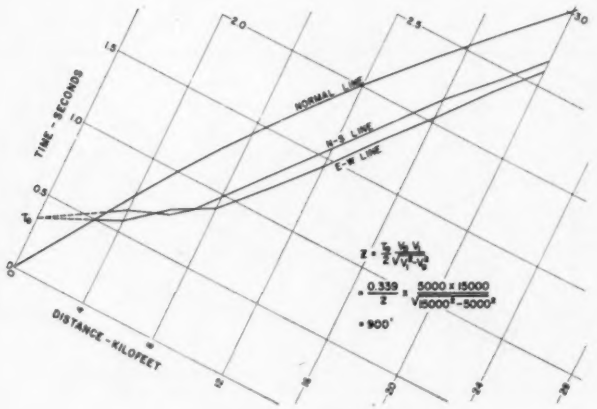


FIG. 14. Diagonal plot of two short-refraction lines across the top of a salt dome.

The approximate depth to salt may be determined by the two-layer refraction method as indicated in Figure 14. The dip may be determined by the deviation of the apparent velocity from that of salt velocity (approximately 15,000 ft/sec), and corrections can be made for depth and position corresponding to the amount of dip.

A preferable method (Figure 15) of determining the depth to salt is by use of the wavefront chart, and the time and distance to the salt break. One-half the time is marked on a transparent time-distance scale calibrated at salt velocity. With the strip horizontal, this time is moved vertically down a line equal to one-half the distance to the salt break until a time match is obtained between the strip and the wavefront chart at the proper ΔT. The depth to the salt in this case is 1,065 ft.

With the depth to salt determined, and the time versus distance data previously recorded, vertical sections are plotted for the two short refraction lines.

A piece of transparent paper that has been blocked in 1,000 ft squares at the scale of the chart is set over the chart, and the starting point is set as described above. Assuming that the profile has been plotted out to 6W, (Figure 16) the time 1.537 sec is observed from 6W to 6E. The average ΔT at 6W is 0.149 which establishes a pivot point on the west shoulder of the salt with a sedimentary time of 0.535. A salt strip is set with a time of 1.002 at this pivot and the locus 6W-6E

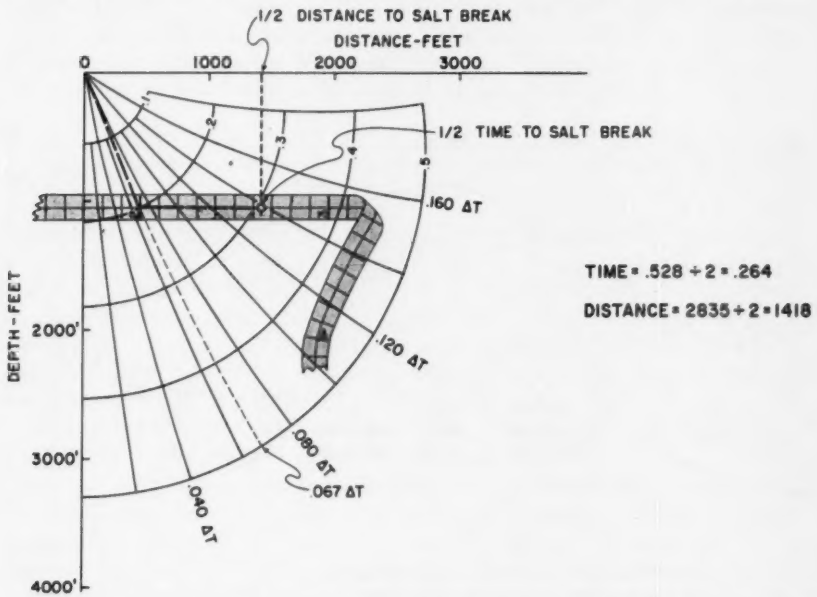


FIG. 15. Preferred method for determining the depth to the top of the salt. If the salt is flat, the depth is 1,065 ft; otherwise the depth should be adjusted for dip.

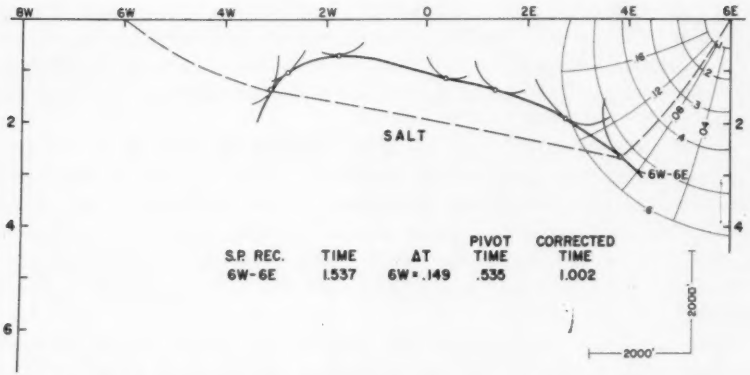


FIG. 16. Diagram showing the method of surface-to-surface refraction plotting. The example, locus 6W−6E, is plotted by subtracting the sedimentary time to the west side of the salt, 0.535 sec, from the total observed time. Time coincidences on the locus are determined between the salt strip pivoted at the west side of the salt and the wavefront chart located at 6E. (The plotting procedure will be shown again for a longer vertical section).

is plotted from time coincidence between the salt strip and the wavefront chart located at 6E. The time from 6E to 8W is 1.820 sec (Figure 17). The ΔT at 6E is 0.096 with a sedimentary time of 0.530, therefore, a time of 1.290 is set on the salt strip at the pivot on the east side. The locus 6E-8W is then drawn as before with a wavefront chart at 8W. It can be assumed at all times that an exit or entry

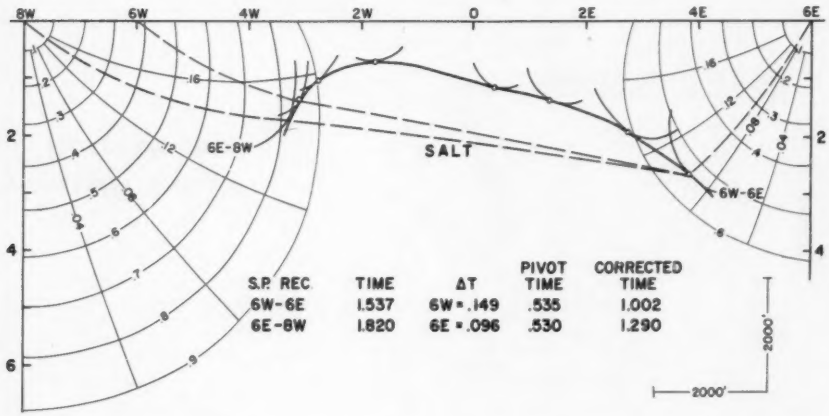


FIG. 17. The next step after Figure 16. A reversed chart is placed at 8W in order to plot the locus 6E–8W. The time to the pivot on the east side of the salt is 0.530 sec along $\Delta T = 0.096$.

point on the salt below the same surface location remains constant as long as the shotpoint or receiver on the other end is not moved more than 2,000 ft. All salt entry and exit points are plotted on raypaths determined by an average of the two ΔT's adjoining that point on that side of the dome. If the ΔT's in one direction vary from those in the other direction, either the dome is asymmetrical relative to zero distance, or the sedimentary velocity varies from side to side.

The shape of the salt on top of the dome is determined from the two short refraction lines. If it is essentially round (Figure 18), radial lines are laid every 20° around the center of the dome. They extend in intervals of 2,000 ft from the

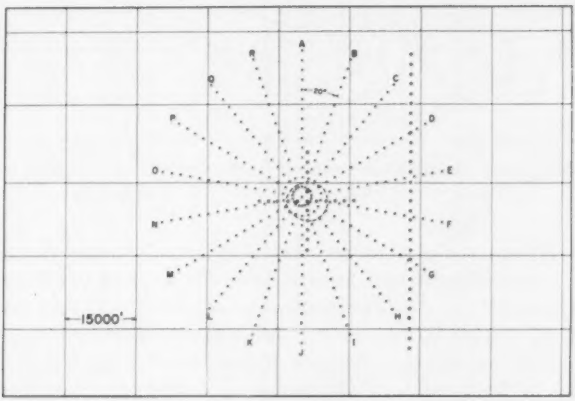


FIG. 18. Layout of detailed surface-to-surface refraction lines, shown by small circles; lines labeled "A" through "R."

center to approximately 30,000 ft beyond the edge of the salt. Depending upon the depth and vertical configuration of the dome, the shooting boat might be held at any one or more points along a radius while the recording boat is moved along the opposite radius. If the salt is quite shallow and the flanks sloping, it could be shot from a point held at the center, while the cable was moved along a radius in 2,000 ft intervals. If the salt is relatively deep, the shooting boat and the recording boat might start at opposite ends of a diameter and move towards each other in 2,000 ft intervals, pass and continue to the ends of the line. Each of the nine diameters would be handled in the same manner.

For all nine lines, water velocities would be determined as previously described, and the distances to each phone at each cable position along a line would be plotted on a diagonal plot versus its first break or later arrival. Slopes would be drawn through the data and a continuous first-break line derived for each line of shooting. Times would then be read from each first-break line at equal distances corresponding to the nominal distance between shotpoints.

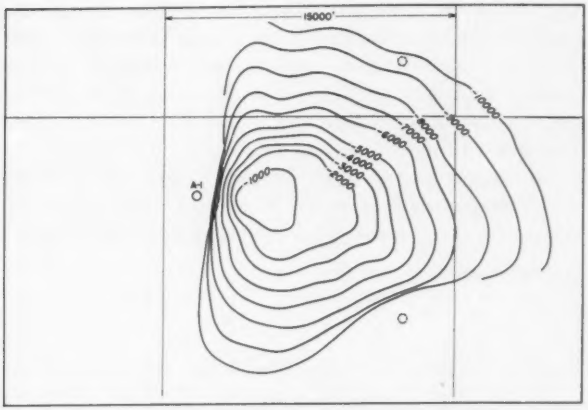


FIG. 19. Map made from surface-to-surface detailed refraction lines. Contour points are taken from salt outlines drawn on the vertical profiles.

Vertical sections are plotted as previously described except that for these longer lines it is possible to plot farther down the sides of the dome. A general shape map (Figure 19) of the salt is made after an outline has been drawn on each vertical section tangent to the vertical loci. From this contour map of the salt, it is possible to recommend a minimum of three wildcat locations for drilling on different sides of the dome in an advantageous location for geophysical exploitation. These are recommended approximately 1,000 ft outside of the salt at the

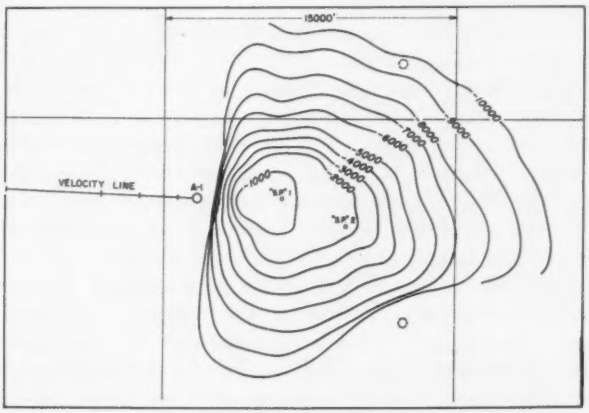


FIG. 20. Location of part of velocity line and salt proximity locations relative to surface-to-surface contoured refraction map.

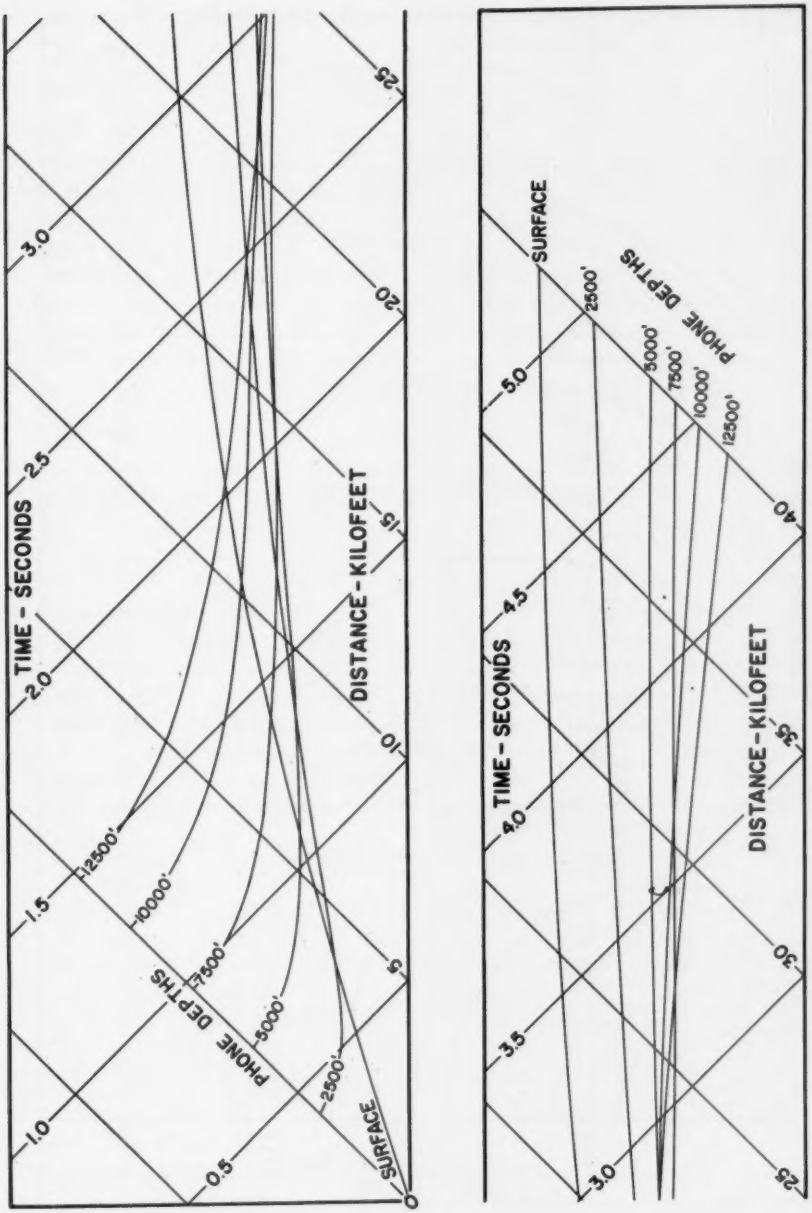


FIG. 21. A total time versus horizontal distance plot for the horizontal velocity survey taken from the flank well.

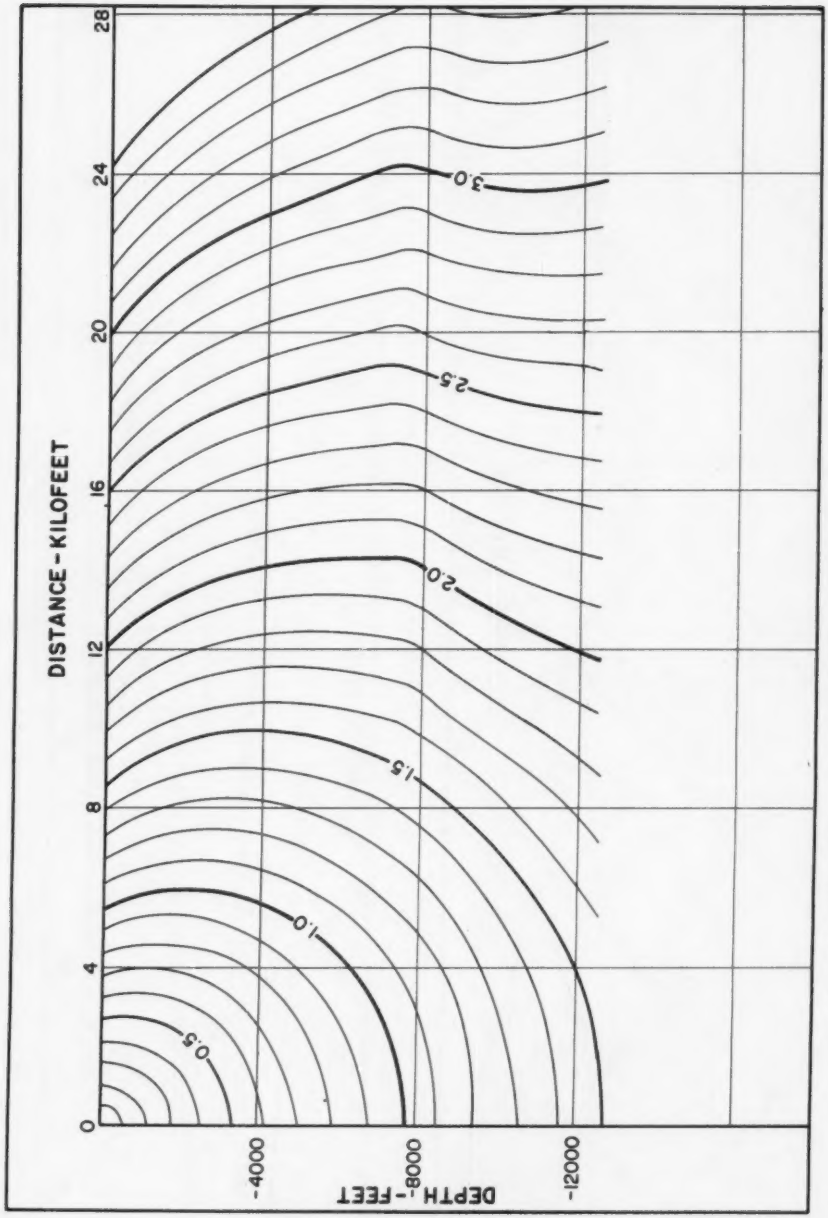


FIG. 22. Observed wavefront chart constructed by joining points of equal time as read from Figure 21.

objective bed. This essentially ends the geophysical exploration phase of the work, and the program now moves into the geophysical exploitation phase.

EXPLOITATION

Velocity

As the A-1 well is drilled, a continuous velocity log is run to total depth before each casing string is set. A velocity line (Figure 20) is shot away from the dome at distances of 1,000, 3,000, 5,000 ft and at 5,000 ft intervals thereafter out to 40,000 ft at approximate right angles to the strike of the salt. Shots are recorded with a phone at 1,000 ft intervals to total depth in the well from each of the above distances. This process may be greatly simplified with multiple phones. A plot of times versus horizontal distance (Figure 21), determined by water breaks, is made for every level. The distances to even 0.1 sec are read on each curve, and these data are used to construct an observed wavefront chart (Figure 22).

Salt Proximity Profiles

At the same time that the velocity line is shot, two salt proximity points (Figure 20) are shot into phones every 500 ft down the hole to total depth from locations near the top of the dome. One salt proximity or "S.P." point is at the center of the surface-to-surface lines, and the other near the far shoulder. A tangent (Figure 23) is drawn to the loci plotted from these data. This profile shows the proximity of the salt to the flank well in greater detail than any of the other shooting. Unless the well was drilled into salt, the upper sedimentary time and salt outline is used from the surface-to-surface refraction shooting. The loci (Figure 24) are obtained by pivoting the salt strip about a pivot at the top of the salt and finding coincident times on special wavefront charts which are made for each level at which phones are located. The velocity layering is determined from the acoustic log and the shooting on the velocity line. Small wavefront charts are then calculated above and below each phone level with an electronic computer.

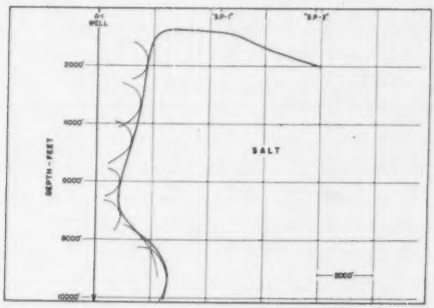


FIG. 23. Outline tangent to all salt proximity loci shot into A-1 well, showing detailed profile of salt on one flank of the dome.

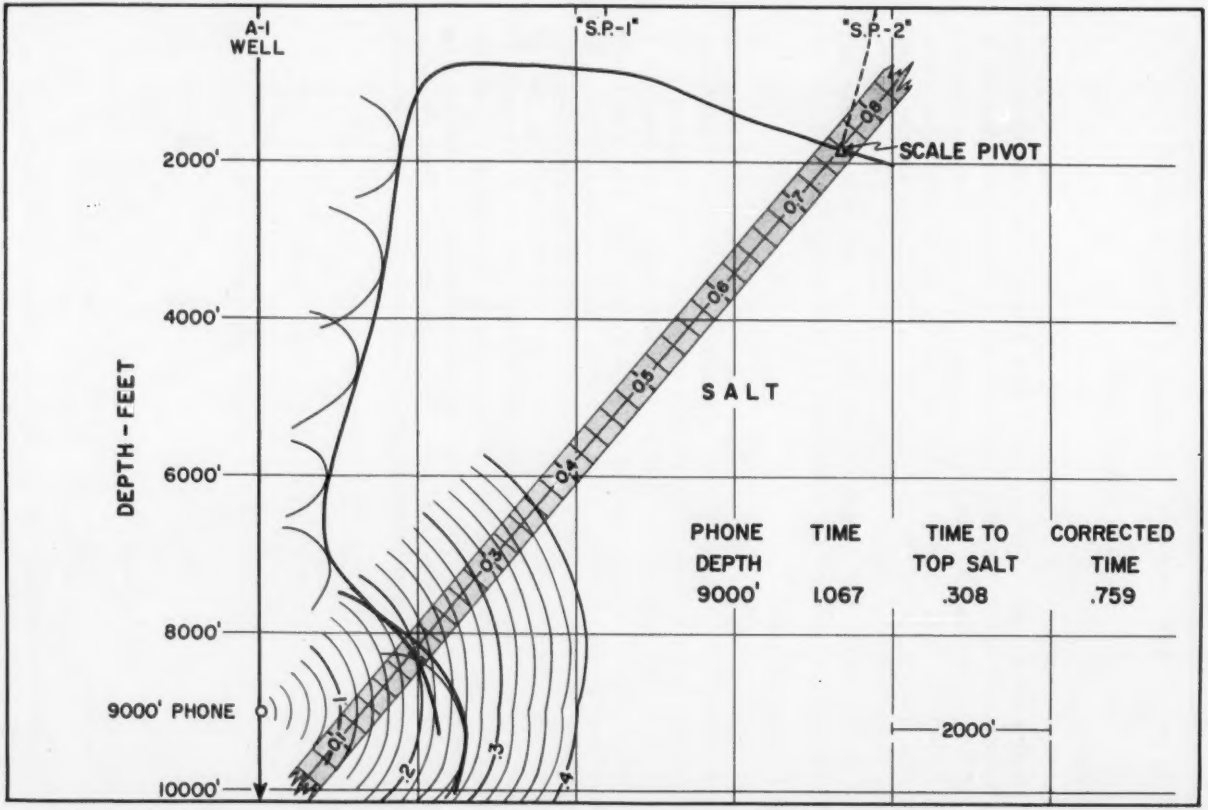


FIG. 24. Method for obtaining loci shown in Figure 23. Velocity control obtained from continuous velocity log in A-1 well and horizontal velocity chart. Data for small charts programmed through an electronic computer.

From the salt proximity profile an offset bottom hole location, A-2, is recommended which will explore the sediments closer to the salt, in this case, under the overhang. Salt will be entered at a vertical depth of about 11,000 ft (Figure 27). It will penetrate about 1,500 ft of salt for use in shooting a fan of lines (Figure 25) across the dome.

Salt Profiles

The purpose of shooting these salt profiles is to obtain greater detail and depth control on the side of the dome opposite the flank survey well. A refraction record (Figure 26) shows two phones 1,000 ft apart, each with two horizontal elements oriented at right angles. These are recorded on flat-response amplifiers

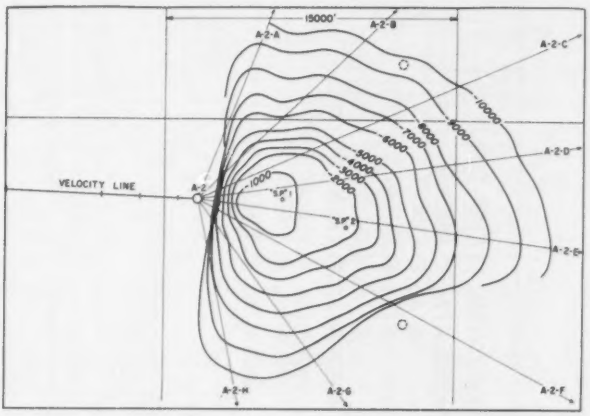


FIG. 25. Location of fan of refraction lines to be shot into A-2 well to profile salt on opposite side with more detail and greater depth.

at two gain levels. A surface phone is recorded at the wellhead both on a flat filter for refraction information and a high-pass filter for water breaks. The water velocity is determined as before and used for distance control. A time-distance diagonal plot is made for each phone level on each line for comparison and to check for continuity, smoothness, and errors. A vertical section (Figure 27) is plotted for each line, and an outline of the salt is drawn tangent to all loci. A plot of the loci for the lower phone on line A–2-E is shown. The number on each locus refers to the approximate shotpoint distance in thousands of ft. Each particular locus (Figure 28) is obtained by setting the total time on the salt strip at a pivot point which is at the true vertical depth of the phone and at a horizontal location projected into the section from the directional log. A wavefront chart, representative of the sedimentary velocity in the direction of the line, is set at the exact distance of the shotpoint and the locus is drawn as before. When

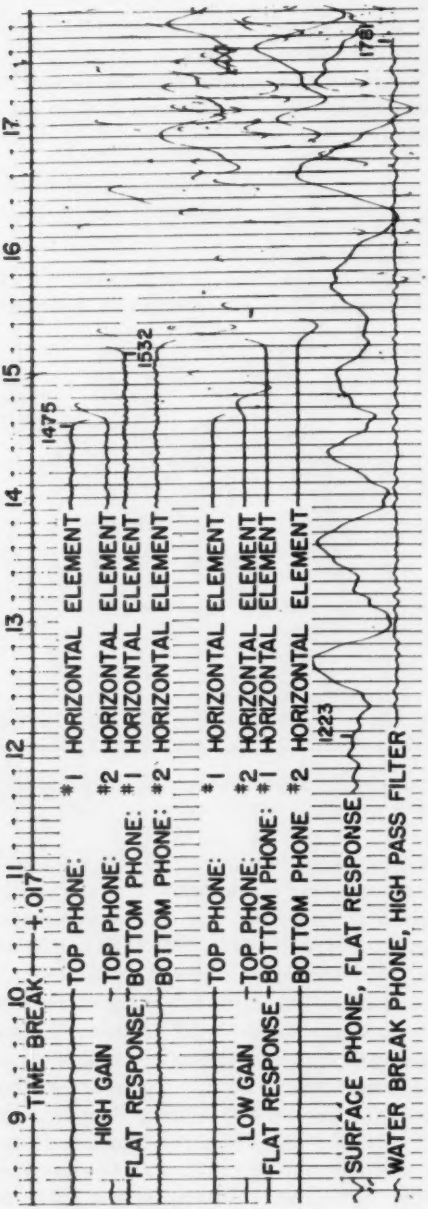


FIG. 26. Seismograph record showing refraction breaks from a pair of phones in salt, top phone: 11,500 ft; bottom phone: 12,500 ft. Two horizontal elements at right angles for both top and bottom phones are recorded on flat response with a high gain and a low gain. A surface break, flat response, is recorded at the well and this phone is also recorded through a high-pass filter to obtain a water break.

two or more phones are used, a vertical ΔT may be used to determine the vertical angle of approach of the wavefront in the salt. The loci and the vertical ΔT's together determine whether the velocities used are reasonable. A picture of the operation (Figure 29) shows the equipment involved. If a mathematical wave-front chart is used, horizontal ΔT's can also be used to check the salt tangent points on each locus.

In order to handle the possibility of sideswipe of the seismic energy, horizontal loci must be plotted for each contour level. This operation is very important where a flank well is used for the mapping. First, a strip representative of the horizontal projection of a wave-front chart (Figure 30) is made for use in plotting

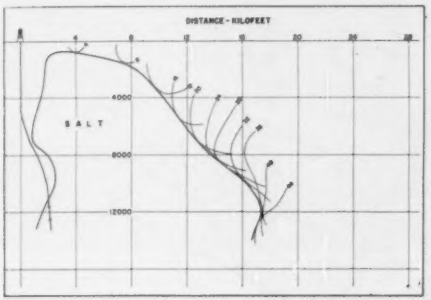


FIG. 27. Outline tangent to all loci from line A-2-E obtained by plotting in a vertical plane.

the loci for the $-6{,}000$ ft contour. Each 0.1 sec crossing of the $-6{,}000$ ft depth at true horizontal distance is marked along one edge of the strip. The data for plotting the horizontal loci (Figure 31) should be taken from the vertical loci on each line. Necessary information consists of the time and distance for the shot-point and phone combination which yields the locus nearest each contour level. Also, a pivot height is set which is the vertical difference between the phone level and the contour in question. It makes no difference whether it is up or down. The time is set on the salt strip on the elevated pivot over the projected position of the phone. The sedimentary strip is pivoted at the shotpoint location and the locus is drawn as before. The picture (Figure 32) further clarifies the procedure and the equipment used. The matching times on the strips arcing around their pivots solve a rather complex, three-dimensional mathematical relationship for all possible least time paths in that plane. The line drawn tangent to a group of loci determines the correct solution for each locus and is the outline of the salt.

A map (Figure 33) is made from a set of loci maps from three flank wells. The map should now be of such detail and depth that exploitation of the petroleum reserves can be completed at a minimum cost. Certainly this is a worthwhile goal around a piercement type salt dome where every location is a wildcat.

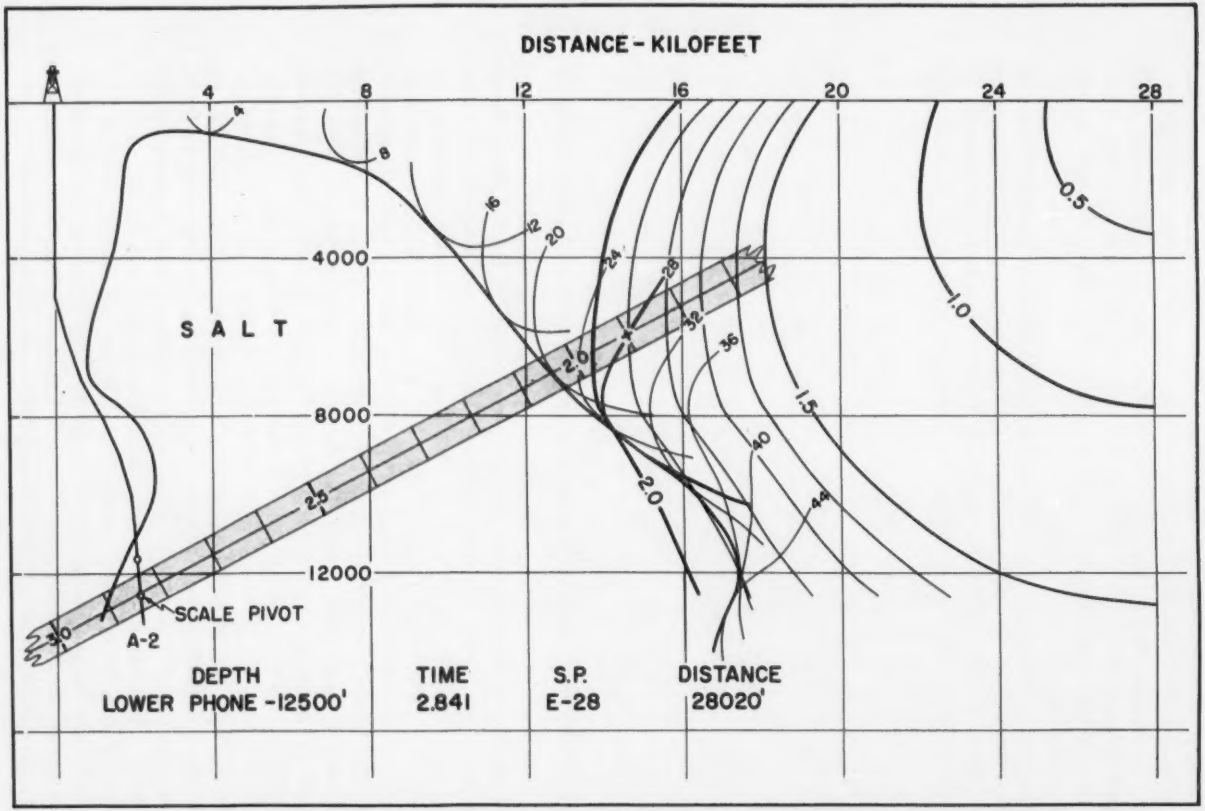


FIG. 28. Method for obtaining loci shown in Figure 27. The observed wavefront charts from B-1 and C-1 are used after they are obtained. A decision may then be made as to the effect of velocity variation. Horizontal loci (Figure 31) may also be plotted using both charts and the differences blended between wells.

FIG. 29. Picture showing use of the equipment involved in plotting vertical loci.

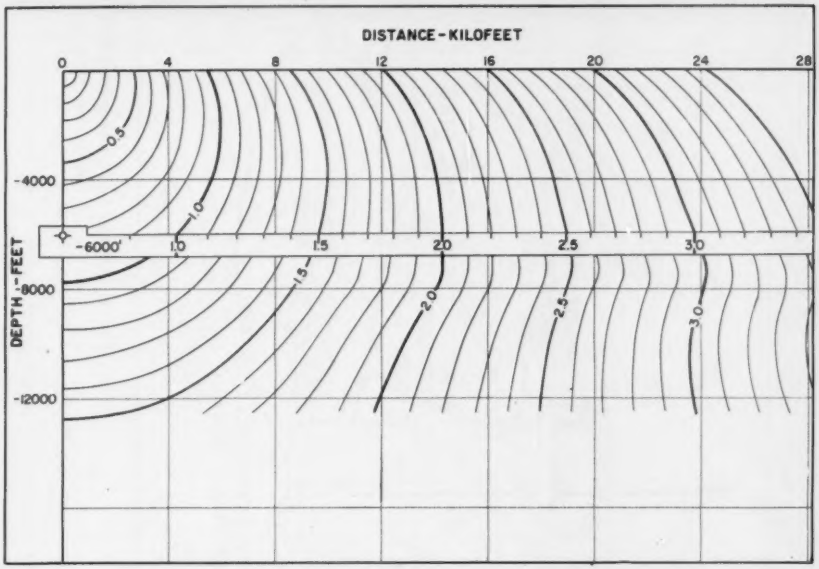


FIG. 30. Method for obtaining a horizontal sedimentary time strip at −6,000 ft from a wavefront chart for use in plotting horizontal loci.

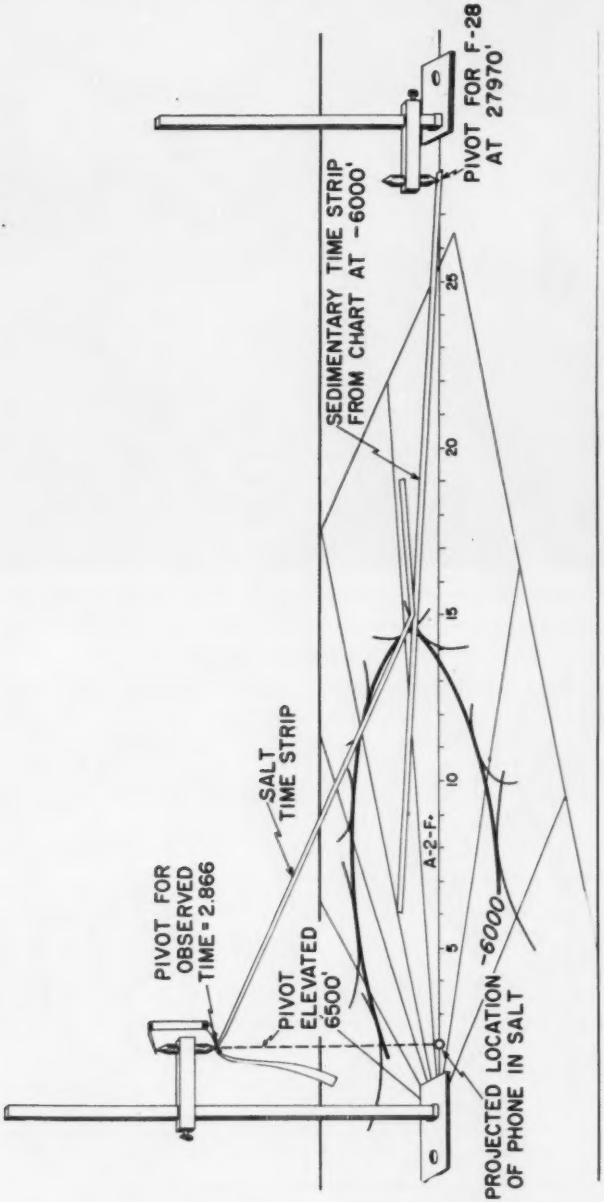


FIG. 31. Method for obtaining horizontal loci using data determined from vertical sections, elevated salt strip, and horizontal sedimentary strips.

FIG. 32. Picture showing the equipment and procedure used in plotting horizontal loci.

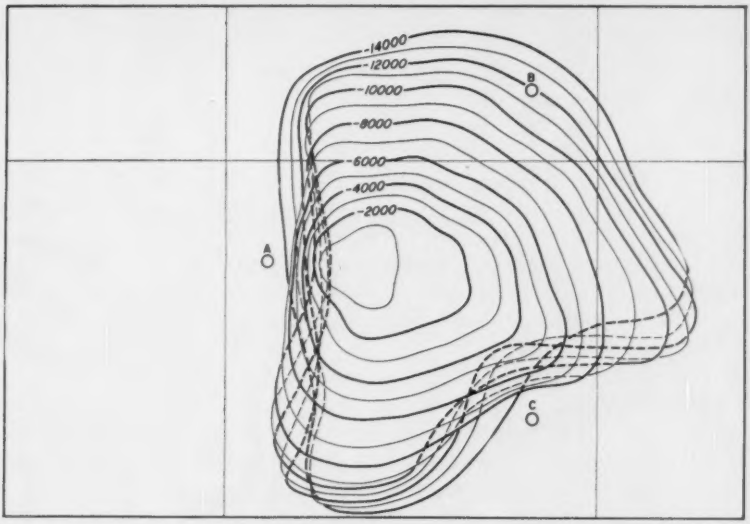


FIG. 33. Final map made after exploitation geophysics has been completed in three flank wells.

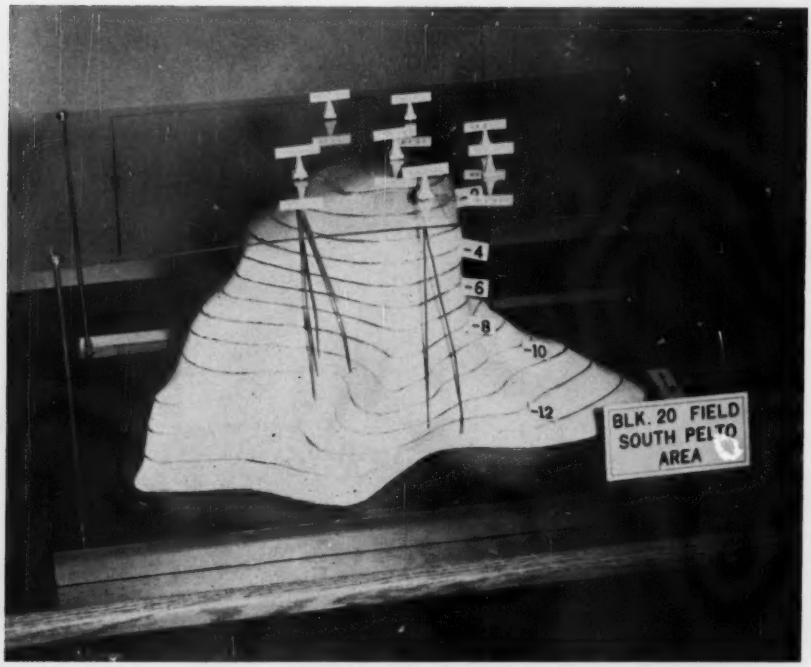


FIG. 34. Picture of an actual salt dome model made from data obtained by methods similar to those described in this paper.

Figure 34 shows a picture of an actual salt dome model made from data obtained by methods similar to those described above.

SUMMARY

The Exploration Phase is conducted on the surface. Reflection shooting is initially used to locate the salt masses. Then short refraction lines are shot to determine the depth of the salt and to locate the center of the top of the dome. A wavefront chart is made from time-distance data obtained from a refraction line shot over a normal section. A number of long refraction lines are shot to profile the flanks of the dome. Locations are recommended from the map resulting from these profiles.

The Exploitation Phase is conducted from flank wells. Velocity lines are shot away from the dome and observed wavefront charts prepared. Salt proximity points are shot to control drilling of deviated wells. A fan of lines is shot to profile flanks on the opposite side of the dome to greater depths. Finally a map is made integrating all of the refraction information.

ACKNOWLEDGEMENTS

The authors wish to thank Magnolia Petroleum Company for allowing them to present this material and particular thanks are extended to Jack Whitley for making the figures.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 168–180

GEOPHYSICAL RESEARCH AND PROGRESS IN EXPLORATION*

J. E. WHITE,† AND FRANK PRESS‡

ABSTRACT

This is the fourth in a series of review papers dealing with technological developments in exploration and with geophysical research at universities and industrial laboratories.

Among the developments in exploration, the use of reproducible recording of seismic records continues to grow, with a trend toward digitizing reflection data for further computation. Refined digital methods have been developed for computation of synthetic seismograms. Well-logging developments have included the appearance of a resistivity logger capable of being pumped down the drill pipe; the availability of more tools for logging seismic velocity, accompanied by laboratory investigations of the manner in which seismic velocity is affected by porosity, fluid content, and other factors; commercial use of the scattered-gamma ray density tool; and further interest in gamma ray spectral logs. Remarkable advances have been made in the techniques of gravity measurement aboard surface vessels and aircraft, although the results are not directly applicable to prospecting. The proton precession magnetometer is being used in commercial air-borne surveys, but the rubidium vapor magnetometer is not available as an exploration tool. The development of a Doppler-positioned navigation method has greatly facilitated air-borne surveys. A ship-borne seep-detector has been outfitted for exploration in water-covered areas.

A review is presented of research on all phases of geophysics at academic institutions in the United States, including laboratory experiments, field measurements, and theory. The review also gives partial coverage of geophysical research at European laboratories, including a discussion of Soviet research as gauged by recent visits to a number of research laboratories in the Soviet Union.

INTRODUCTION

At the Annual Meeting of the SEG in Denver in 1955, the SEG Research Committee sponsored a paper which reviewed significant developments in exploration technology during the previous year. In 1956 the second paper in this series was given, covering exploration technology but featuring a review of research projects at universities and other non-commercial institutions relating to exploration geophysics. The third paper sponsored by the Research Committee, presented at the Annual Meeting in 1957, reviewed recent technological developments in Europe, as well as developments in exploration methods in the United States. Since no paper was given in 1958, the present paper will cover a two-year period, attempting to describe briefly the main developments in exploration methods within the United States; to review geophysical research at academic laboratories within the United States; to mention some research topics currently being investigated at European laboratories, without any claims as to completeness of coverage; and to pass on some impressions gained during recent visits to Soviet geophysical research laboratories.

* Presented at twenty ninth International Meeting, November 9, 1959. Manuscript received by the Editor October 8, 1959.

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DEVELOPMENTS IN EXPLORATION TECHNOLOGY

Seismic Prospecting

Techniques for reproducible recording of seismic records, which have been described in earlier review articles of this series, have undergone further development by many manufacturers of seismic equipment and have gained such widespread acceptance that the use of magnetic recording may well be considered standard. Several equipments exist which will reliably produce a time-corrected record-section, in wiggle-trace, variable area, or variable density presentation, usually in a central office playback facility. Miniaturization of recording and play-back equipment is proceeding rapidly, making it easier to carry out the complete record analysis in remote field locations.

Digital computers offer an attractive means of making routine computations on seismic data, as evidenced by activity among several research groups during this period. Starting with reflection times read from records in the conventional way and punched into cards, one group has used a digital computer to compute true depths for as many as 13 reflection events, with automatic plotting of the depth points. Velocity functions may be changed readily, and cross-sections with some chosen reflection as a datum can be prepared easily. The time-consuming operation of picking the reflection times and punching them into cards has been avoided by another research group, who have developed an analog-to-digital converter which senses any selected trough and punches the reflection time automatically. The interpreter indicates on a monitor record the troughs of interest, and then the converter makes the time pick to an accuracy of one millisec from the corresponding magnetic tape record. Still another group has developed the digital computer routines to compute migrated cross-sections from such digital reflection-time data, which are then plotted on a specially designed geophysical plotter. This instrument plots on a 40×40 inch surface at a rate of approximately one point each $1\frac{1}{2}$ sec. When plotting seismic cross-sections, it plots a reflection as a line segment of suitable length and inclined at a dip angle controlled by the input. Reflection quality is indicated by variation of the line "weight" and texture. A central symbol is printed at the x, y coordinate point of the reflector. In addition to seismic cross-sections, the plotter is also applicable to mapping problems in which x and y are surface coordinates, and derived or measured parameters may be posted by the digital print.

Digital computers have made possible a major refinement in the application of synthetic seismograms to problems of seismic interpretation. Commercial services now offer synthetic seismograms obtained by electrical filtering of continuous velocity logs, producing a trace equivalent to single reflection at each interface of a wavelet whose shape can be selected. During the last two years, at least three research groups have described digital programs for computing synthetic seismograms from velocity logs including all multiple reflections, lead-

ing to a number of significant conclusions. Being able to compute the multiple reflections separately and to compare them with the single-reflection contributions is of considerable value. The effect of multiple reflections on the transmitted pulse can also be obtained, and it was shown that passage through a complex section of layers may change the waveform drastically. This means that a reflection from a single isolated interface at depth may be quite complex, simply because the pulse has traversed the complex overlying bed twice, down to the reflector and back to the surface.

No new field techniques for seismic prospecting are to be reported, but perhaps some comments on methods described in earlier review articles are in order. The "Sonoprobe" described earlier has been used further in exploration of water-covered areas, and another group has developed instrumentation for obtaining continuous profiles of shallow sediments in water-covered areas, operating from a single boat at speeds of three to eight knots and portraying beds as much as a 1,000 ft below the bottom. This equipment is known as the "Sparker" from the fact that its sound source is a 10,000 volt spark fired underwater, usually at a repetition rate of two to four sparks per sec. Little information beyond that given in the last review article could be obtained on the seismic method utilizing a frequency-modulated continuous earth vibrator[1] in place of dynamite, although it is apparently undergoing further development and evaluation. Weight-dropping has gained wider acceptance during this period, there now being 12 domestic crews and two or three foreign crews in operation.

Gravity Measurements

Undoubtedly the most exciting developments in the techniques of gravity measurement have been the demonstrations of accuracies which can be achieved aboard surface vessels and in airplanes.[2] The LaCoste and Romberg submarine or surface ship gravity meter has low enough drift and is capable of averaging the 50,000-mg accelerations of a surface ship well enough to permit readings to be taken with a precision of about one mg. Ship navigation then becomes a controlling factor, since a one-mile error in location can give an error of about one mg and an error in ship speed of one knot can give an error of about seven mg. From a number of cruises, it is concluded that gravity surveys from surface ships can be made to an accuracy of two mg. With the addition of an analog computer to speed up the meter reading process, several runs aboard a KC-135 jet airplane at Edwards Airforce Base and another set of tests aboard a B-17 aircraft indicated an accuracy of about ten mg limited by the accuracy with which the position of the plane could be determined throughout the flights. The quality of the results is adequate for geodetic purposes and possibly for some special geophysical applications.

[1] Editor's Note: See page 95, this issue.
[2] Editor's Note: See page 181, this issue.

Magnetic Methods

The proton precession magnetometer has been used in many field surveys for research purposes, some of them in connection with the International Geophysical Year. One company has tailored its instrumentation to oil prospecting and offers the proton precession magnetometer as one of its family of aerial surveys, reporting very good performance in every way. Among the advantages of this instrument are its light weight, durability, and absolute calibration. Among its disadvantages are the fact that readings cannot be taken much oftener than twice a sec, which may yield an undesirably low density of observations in an aerial survey, and the fact that only the magnitude of the total field is obtained, with no possibility of measuring the individual components of the field separately.

Another principle applicable to the measurement of the earth's magnetic field was described before the SEG in 1958, but its adaptation to geophysical prospecting usage is apparently at a stand-still. This magnetometer depends on the optical detection of magnetic resonance in rubidium vapor. In one version, the output of a photocell, due to polarized light which has traversed the rubidium vapor, is fed back to a coil surrounding the rubidium cell in such a way that the system oscillates at the Larmor precession frequency. Like the proton precession magnetometer, it indicates the magnitude of the total field. It has the advantages of higher sensitivity and of being able to follow rapid fluctuations. If these features should be especially needed, the ruggedness, small size, and low power drain of the rubidium vapor magnetometer mark it as a likely candidate for field use.

Well-Logging

As a continuation of the trend pointed out in the last review article, the popularity of seismic velocity logs has continued to grow, aided by the improved availability of velocity logging equipment. Instrumental developments include the multi-receiver tool, which permits a choice of the interval over which the velocity is averaged and hence over the resolution. In addition to continued use of velocity logs as an aid to seismic interpretation, both laboratory measurements on cores and empirical field comparisons have shown the velocity log to be an effective measure of porosity[3] in consolidated formations with intergranular porosity. Although no report has been given of a systematic attempt to use the attenuation of the seismic pulse, as well as its transit time, it has been noted that a virtual disappearance of the received signal may occur in highly fractured zones or in unconsolidated formations bearing gas.

The density logging tool which makes use of a suitably collimated gamma-ray source and scintillation detector has reached the stage of commercial availability, although experience with density logs is still somewhat limited. The close connection between rock density and porosity make this tool very attractive for

[3] Editor's Note: See page 250, this issue.

formation evaluation, especially in cases where the reservoir rocks may contain variable amounts of shale. It is expected that use of this tool will continue to grow.

A very significant development in nuclear well logging is the experimental demonstration that a borehole particle accelerator can indeed be engineered to meet the rigorous requirements of ruggedness, small size, and lower power consumption imposed by the well logging application. This has made possible the downhole generation of 14-mev neutrons, suitable for neutron-activation of elements around the well. Detection and spectral analysis of the resulting gamma-rays offers the possibility of a reasonably complete analysis of the main elements in the rocks around the borehole. From the standpoint of direct indication of oil saturation, oxygen activation looks particularly attractive, since water and all rocks have an abundance of oxygen, whereas oil has none. Although experimental logs have demonstrated the soundness of this approach, much development remains before it can be considered a proven commercial log.

It should be mentioned that an API subcommittee has sponsored a test facility for calibrating nuclear logging tools and is setting out to standardize scales and sensitivities of neutron and gamma-ray logs from the various companies.

One noteworthy instrumental development during this period is an electric-logging tool capable of being pumped down a drill pipe and out through the bit, thus permitting the logging of a freshly drilled section of hole before mud invasion has progressed and without requiring that the drill stem be removed. A magnetic recorder running for 80 minutes records resistivity and SP logs, after which the tool is pulled out on a wire line. This tool has been successfully field-tested, and a manufacturer is preparing to make it available commercially.

Another development in electric logging which has been successfully field-tested is referred to as "reverse-wetting logging." Laboratory measurements showed that the resistivity of an oil-saturated core is substantially increased by the addition of an agent which tends to make the core preferentially oil-wet, whereas the resistivity of a water-saturated core was unaffected by the agent. As a field test, resistivity logs were run in a well, the well was then reamed with a mud containing the reverse-wetting agent, and the resistivity logs were run again. As expected, the oil-bearing zones showed increased resistivity.

Seep Detector

An effective and inexpensive technique for locating gas seeps[4] has been developed for use in water-covered areas. As gas bubbles rise to the surface, small amounts of methane are dissolved in the water, and currents spread this methane-enriched water into a long plume. A boat samples the water continuously, operating on a grid laid out at right angles to the current. Gas is broken out of solution and trace amounts of methane are detected by a non-dispersive infrared analyzer.

[4] Editor's Note: See page 275, this issue.

The low cost of this method makes it attractive for localizing areas of interest for subsequent coverage by more expensive exploration methods.

Doppler Positioning

A major advance in the conduct of aerial geophysical surveys is the adaptation to this purpose of navigational systems used by virtually all high speed military-jet flights and many commercial planes. It makes use of the fact that when a radar signal from the moving plane is reflected back by objects along the ground, the frequency of the returned echo experiences a Doppler shift which depends on the speed of the plane. By sending out radar beams in four directions, the true ground speed is obtained, and computers keep track of the speed and direction, thereby indicating true position of the plane at all times with surprising accuracy. Thus, pre-selected traverses can be run, even over terrain devoid of land marks, and without need of ground stations.

ACADEMIC RESEARCH

From the large program of geophysical research in the universities, we have selected topics of special interest to readers of GEOPHYSICS. Many important fields, such as isotope geology and mining geophysics, have not been covered. This report could not have been completed without the help of our colleagues at the following universities: Harvard, Columbia, M.I.T., U.C.L.A., California, Stanford, Penn. State, Minnesota, British Columbia, Wisconsin, Toronto, Utah, and Caltech.

The major trends in academic research during the past few years have emphasized world-wide field measurements, the use of electronic computers in data reduction and analysis, and the development of improved instrumentation.

Partly due to the stimulus of the International Geophysical Year and partly a reflection of increased interest in geophysics in the universities, the past two years have seen expanded efforts in world-wide field studies. A wide variety of methods were employed including explosion seismology, earthquake seismology (particularly surface waves), gravity observations, air-borne and ship-towed magnetometers, submarine geophysical methods (coring, photography, echo-sounding, heat flow).

Extensive surveys have been made of the oceans, including remote seas not heretofore reached by modern research ships. About 1,000 deep sea seismic refraction profiles have been made in the past two to three years. In cooperative ventures such as the recent search in the Atlantic Ocean for a possible site for the Mohole, three or four ship refraction profiles having lengths as great as 70 km were obtained. The deep-sea work is now directed toward more careful measurements to reveal variations in the physical properties of sediments, crust, and mantle from one region to another.

IGY results in Antarctica, based on a combination of explosion and earthquake data, point to the conclusion that the eastern part of Antarctica is conti-

nental in structure and that the western half consists of shelves, islands, in an ice-covered archipelago. Gravity and reflection seismology show average ice thickness greater than had been assumed. Extensive parts of western Antarctica and coastal regions have ice extending to below sea level.

Studies of the continental crust have seen the use of improved apparatus for recording explosions and the development of new techniques to exploit earthquake surface waves more fully. The importance of the intermediate, often masked, crustal layer in the interpretation of structure was appreciated more fully as a result of work in the USSR, and this layer has now been traced in the Great Basin and in the Canadian Rocky Mountain foothills.

The use of phase velocity of surface waves to reveal regional crustal structure is receiving wider application. The striking correlation found between Rayleigh wave phase velocity and gravity anomaly in North America has important implications regarding isostasy.

An increasing use of geophysical methods for the solution of geological and glaciological problems is noted. Explosion seismology and gravity methods have been used in reconnaissance explorations of geological basins, and in delineating the thickness of glaciers.

Instrumental seismology emphasized further development of long period seismograph systems. Long period pendulums (30–300 sec) and galvanometers (500 sec) were designed. Special transducers, networks and notch filters were used with excellent results. These new instruments, by extending the seismic spectrum, provide data useful in obtaining the properties of the outer layers of the mantle and crust as well as information on the mechanism of the focus.

The analysis of records from these instruments and their theoretical interpretation has yielded exciting results. It was demonstrated from surface wave data that the Gutenberg low velocity zone in the mantle is a world-wide phenomenon. The phase velocity method of exploration was extended to make possible the analysis of crustal structure variations across an entire continent and a significant correlation was found between phase velocity and gravity anomaly.

Surface waves from earthquakes and large explosions continue to be a fruitful field for research. Higher mode propagation has been discovered and analyzed and the structure of the continents, Antarctica, and the deep-sea floor has been scrutinized by these techniques. Advances in the theory of these waves were made and exploited, and electronic digital computers contributed much to these efforts.

Nuclear explosions have provided amplitude and travel time data of seismic body waves which will make possible the delineation in finer detail of the internal constitution of the earth.

Ultrasonic model seismology has progressed to the point where two-dimensional models with continuous variations in density and velocity may be conveniently fabricated.

The need to establish on a firm mathematical foundation the theory of diffrac-

tion and scattering of elastic waves was recognized and much progress was made. Radiation from different types of sources, scattering of impulsive waves from spheres, cylinders, transmission at corners, and effects of topographic irregularities are some of the problems which have been attacked. Some new mathematical techniques and extensions of old methods were employed.

The report of the Panel on Seismic Improvement (Berkner Panel) has done much to stimulate research in mathematical methods of operating on seismograms to reveal the properties of the source and the propagating medium. It may be recalled that this panel was originally appointed by the President's scientific adviser, Dr. Killian, to study the possibility of improving seismic methods of identification of nuclear explosions. The panel immediately recognized that a broad program of fundamental research was needed. Although this program is now getting underway, preliminary results have shown that information and communication theory when coupled with good understanding of the physics of wave propagation can lead to important progress.

Developments in marine gravimeters have reached the point where important data from these instruments are already being obtained. The Worzel adaptation of the Graf Sea Gravimeter completed a successful program of observations on an 1,800 ton fin-stabilized vessel equipped with a stable platform. Results for the LaCoste marine gravimeter were described earlier.

Reduction of gravity observations and interpretation of anomalies were programmed for electronic digital computers.

Magnetic anomalies revealed in marine surveys have shown interesting patterns for which the tectonic significance has yet to be found. The possibility that displacements along faults may be measured from anomaly patterns has been demonstrated. Paleo-magnetic studies are in the stage where many measurements with wide geographic distribution are needed and are being obtained. Interest is growing in low frequency (.01–100 cps) magnetic fluctuations and these are being measured with instruments suitable for correlation studies over large distances. Research in the use of magneto-telluric methods of exploration is continuing. Particular emphasis seems to be on field testing.

RESEARCH IN THE SOVIET UNION

We could not hope to cover the large geophysical research program in the USSR adequately. What follows is compiled mostly from the reports of Drs. Yost and Press on their recent trips. It is not an evaluation, but a fragmentary review of selected fields in which original work is being done of interest to readers of GEOPHYSICS.

There is much emphasis on the use of the dynamic characteristics of elastic waves to obtain more information about the sub-surface than time data alone will provide. For example, the absorption coefficients of refraction arrivals are determined and interpreted to distinguish between granitic basement and gneissic basement. The use of absorption coefficients to distinguish between high velocity

sedimentary layers and basement is also being studied. Attempts are being made to relate variations in absorption coefficient to variations in porosity. Absorption coefficients as determined in acoustic well-logging devices is an additional parameter that is being used. The acoustic logging tool consists of a bank of three equally-spaced receivers with a transmitter on either side. The device is being instrumented for uphole recording of five parameters: compressional velocity, shear velocity, absorption coefficient for compressional waves, frequency, and wave length of the recorded signal.

Spectrum analyses of refraction and reflection arrivals in the range 20–400 cps are being used for diagnostic purposes, such as determining layer thickness. Theoretical studies and experimental work on the variation of amplitude of refraction arrivals as a function of velocity contrast is being carried on. Field data were cited in support of the theoretical result that the lower the velocity contrast the greater the refraction amplitude. Research is being conducted on multiple refractions and on composite body waves such as PPS or PS. These waves are distinguished by their spectrum as well as the orbital motion at the surface. This work is being carried out in the exploration frequency range for possible application as a field tool. Shear wave reflections at depths of about 2,000 meters were obtained from a dynamite blast.

Correlation refraction shooting is receiving much emphasis. This method is used in exploration for petroleum as well as in studies of the earth's crust. These studies use long refraction profiles whereby a given wave group can be traced over large distances. We were told of one profile having a length of 200 kilometers with an observation at every 200 meters. Use is made of amplitude changes and apparent velocity for diagnostic purposes. This technique has been particularly effective in delineating velocity changes within the crust. The field procedure is to lay down a spread of approximately 10 to 60 groups of geophones, the group separation being 200 meters. Each group consists of four geophones, separated anywhere from 8–15 meters, depending upon the local background noise conditions. Charges of less than 1,000 lbs of TNT are detonated in lakes and by repeated shooting, a profile of 300 or 400 kilometers in length is achieved. The geophones have a natural frequency of nine cps and the overall amplification of the system is ten million in the frequency range 6–9 cps. Radio communication is maintained between the shotpoint and the recording position so that the explosion is delayed if local wind noise prohibits high sensitivity operation of the detectors. The operations are carried out usually in the middle of the night when wind noise is at a minimum, and in regions remote from industrial sites. Thus by putting great effort in their field procedure, the Russians have been able to minimize the effort required at the shotpoint. It is claimed that refraction arrivals from the crustal layers as well as from the Mohorovicic discontinuity can usually be correlated over large distances. The very interesting result is reported that compensation can occur at the level of the Conrad dis-

continuity as well as at the Mohorovicic discontinuity, and that the complex behavior of these interfaces is reflected in the gravity picture.

Soviet seismologists have been interested in the use of high frequencies in exploration seismology for some years now. They have been working with frequencies as high as 500 cps. At these frequencies they feel they can do mapping to a depth of 100 meters. In the frequency range 100–200 cps, they have mapped to depths of 2,000 meters. The sources are generally dynamite shots of two–five kg, or some large electromagnetic transducers. The shallow work at high frequencies is primarily designed for locating ore bodies. They have been able to resolve satisfactorily ore bodies 20 meters wide at a depth of 200 meters even when the ore body was very thin.

It is surprising that Soviet work in submarine geophysics was begun only a few years ago, and yet the experimental techniques and results are now at a level comparable to those in the United States, where this field of research was pioneered some twenty years ago. Refraction seismology, topographic surveys, magnetic and gravity observations constitute the tools used in the exploration of such important structures as the Okhotsk Sea, the Kuril Islands, and the Kuril trench.

Research in electromagnetic methods of prospecting is being prosecuted. With one instrument, having a variable oscillator covering the frequency range 0.05–300 cps, it is claimed that fairly reliable mapping can be achieved to depths of 2,000 meters. Amplitude and phase comparison yield the basic data. Telluric currents and naturally variable magnetic fields are also being employed.

An interesting research program in geodynamics involves field measurements, theoretical studies, and model studies relating to tectonics. This closely coordinated approach to the problems of geodynamics from three different directions is unique. Materials such as photo-elastic gelatins and viscous fluids were used to model tectonic processes. The photo-elastic effect was used to measure the deformation. Studies of uplift and subsequent relaxation, as well as thrusting were underway.

SOME EUROPEAN RESEARCH ACTIVITIES

The following comments on geophysical research in Europe are based on recent visits by Dr. White to four research laboratories which place a major emphasis on petroleum exploration.

The program of the British Petroleum Research Centre, Chertsey Road, Sunbury-on-Thames, Middlesex, England, includes diverse topics in geophysics and well logging, as parts of a broader program of research in exploration and reservoir engineering.

Seismic research includes both theoretical and experimental attacks on the generation of seismic waves by explosives, with special attention to the motion very near the shot. Experimental field refraction surveys have been carried out

and the recorded amplitudes and frequencies compared with theoretical solutions. The refraction process has also been studied by means of seismic modelling, in one case utilizing barium titanate transducers in a fluid layer overlying a solid refracting medium. The Centre has a Burroughs E101 digital computer which is often used in the conduct of the theoretical work.

Relevant to the development of instruments for operating seismic crews, the Centre has environmental test chambers, a mechanical vibration table, and a shielded room. A moving van serves as a mobile laboratory for field trials.

Among other geophysical research topics is the development of a borehole gravimeter, which appears to be well along toward conquering the levelling problems, temperature effects, sensitivity requirements, and other rigorous demands to be met by this tool.

Well logging research includes the development of a neutron-gamma ray tool equipped for pulse-height analysis, comparing the output of a channel set to detect the gamma rays from chlorine with the output of a channel which accepts the broad spectrum of neutron-induced gamma rays from all elements. This is aimed, of course, at locating oil-water contacts. This group is also developing a dip-meter which uses 12 "trumpet-log" electrode buttons spaced around a circumference of the tool. These electrodes are sampled sequentially and the output used to intensity-modulate the time base of an oscilloscope, the brightness corresponding to resistivity. The resultant traces are recorded on a film strip which moves as the tool moves in the hole, producing a pattern on which the dip can be measured. If desired, the film can be bent into cylindrical shape, thus presenting a picture of the wall of the hole.

The program of the Royal Dutch Shell Laboratories in Delft includes topics in geophysical research, as well as geology, sedimentology, and geochemistry. After completion of a new building in 1961, this laboratory will handle the complete subjects of exploration and production research, which will include well logging research now being carried out in Amsterdam.

The electronics section has environmental test chambers and equipment for thorough operational check of seismic systems prior to shipment to the field. The function of this group also includes design of equipment, such as a transistorized refraction amplifier.

Two experimental seismic crews operate from this laboratory. Research interests have included refraction interpretation and the generation of seismic waves. A digital program permits the computation of synthetic seismograms without multiples, with multiples at depth but with no surface reflection, or with both multiples and a surface reflection.

The laboratory of Compagnie Générale de Géophysique located at Montrouge, Seine, France has primary responsibility for developing and maintaining equipment for 50 or 75 geophysical crews, conducting training schools for observers and interpreters, and doing research on new instruments and interpretation methods.

One instrumental development of this group is the "Toran" radiolocation system for geophysical surveys. Two "focal point" transmitters located at known places transmit in the two megacycle band on unmodulated carrier frequencies which differ by about 100 cps. A fixed monitor receiver detects this beat frequency accurately and transmits it to a mobile receiver, whose position is to be determined. The mobile receiver also detects the beat frequency between the two focal point transmitters. A comparison of the phase of the beat frequency as measured at the monitor station and the mobile receiver serves to locate the latter on a particular member of the family of hyperbolas having foci at the known locations of the focal point transmitters. A second pair of transmitters provides a set of intersecting hyperbolas, and the phase comparison relative to the second set then locates the mobile receiver.

Research on interpretive methods has included theoretical investigations of the effects of vertical dikes and dipping beds on resistivity surveys, and special attention has been given to the principles underlying the application of telluric currents to prospecting. A close relation between theory and field application is maintained.

Seismic research has included detailed field studies to determine the behavior of extremely large patterns of shots and detectors. Play-back facilities at Montrouge consist of an Electro-Tech., Carter MT 4 group, and a Seismac installation with some added peripheral equipment. In order to get the most from reproducible recording, various record presentation methods are compared and an effort is made to see what benefits can be obtained by extreme filtering. Synthetic seismograms have been computed on their IBM 650 digital computer, including the effects of multiple reflections. In addition to its use in the routine calculations for Toran chains and for interpretation of electrical prospecting, the IBM 650 has been an invaluable aid in the calculations required in gravimetric and magnetic interpretation employing the methods of reduction to the pole.

Geophysical research at the Institut Francais du Petrole, Rueil Malmaison, Seine et Oise, France is one facet of a varied program covering exploration, oil recovery, and chemical processing. The newer buildings have been designed to blend with the original buildings of the estate on which the Institut is located, and fountains and gardens continue to add their charm to the surroundings.

Seismic research here also includes the production of synthetic seismograms,[5] actually by three methods. In one case, the synthetic seismogram is obtained by inking one side of a continuous velocity trace to provide a variable-area film, feeding the photo-cell output through a circuit which takes the logarithm of the voltage, and then sending the signal through a HTL Time Domain Filter, in which the sensitivities of the heads have been adjusted to portray the desired basic reflection waveform. Synthetic seismograms including multiples are also obtained digitally on an IBM computer. The other method might be called "one-

[5] Editor's Note: See page 106, this issue.

dimensional seismic modelling." An ultrasonic pulse of the desired waveform is sent down a brass rod in which the cross-sectional area has been machined in accordance with a continuous velocity log, and the reflection of this pulse then corresponds to the seismic field record, including all multiple reflections. Elastic waves in plastic plates have been used to study diffraction effects near faults and the properties of surface waves. Refraction interpretation is of interest.

The Institut is well equipped to make seismic record sections, having in operation a Carter play-back unit and a Seismac installation. They also have an experimental crew in the field.

GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 181–202, 10 FIGS.

TESTS OF AN AIRBORNE GRAVITY METER*

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ABSTRACT

Gravity measurements have been made in an airplane and a contour map using 20 mg interval constructed for 12,000 ft elevation. The LaCoste and Romberg instrument used is similar to that recently tested on a surface ship. The meter was installed in a B-17 aircraft equipped with APR (precision radar altimeter) and aerial mapping cameras for the accurate navigation needed for determination of the centrifugal (Eötvös) and elevation corrections. A series of nine lines over the Imperial Valley gave results believed to be accurate to about 10 mg or better as indicated by (1) the general consistency of the contour map and its similarity to a free air gravity map drawn from ground data, (2) repeat observations over almost the same courses, (3) agreement of independent values at line crossings (with Eötvös correction differences of as much as 2,000 mg), and (4) agreement with values calculated from ground gravity stations. Short period disturbances due to accelerations of the airplane are averaged over a certain time interval. This results in an "uncertainty principle," in that the accuracy of observation increases as this time interval is lengthened, but details of the gravity variation are lost due to the increased distance traveled during each measurement. The values reported are for an averaging time of approximately three minutes corresponding to a travel distance of about ten miles. The quality of the results is adequate for geodetic purposes and possibly for certain regional geophysical problems.

INTRODUCTION

During the past ten years, gravity meters have been built to operate with successively greater degrees of motion. The problem was first encountered in underwater gravity measurements because of small vertical motions of the bottom as the load of overlying water changes with passing waves. This problem was successfully met in an instrument in which the gravity meter element acts as a seismograph and, through a servo-mechanism, actuates an "elevator" which moves the gravity meter unit vertically with respect to the case, and in this way counteracts the up-and-down movements of the case itself (LaCoste and Romberg, 1952). Following the successful development of the underwater meter, a project was started to develop a gravity meter which could be used in a submarine as a substitute for the Vening-Meinesz pendulum apparatus. The amount of vertical motion is much greater in this application and also a new problem is introduced in that the meter is subject to horizontal accelerations. This requires some means of reference to the true vertical in order to measure the vertical component of gravity. In the submarine meter (LaCoste, 1959) the instrument itself is suspended in gimbals and is free to swing laterally. In the

* Presented at the 29th Annual Meeting of the Society, Los Angeles, California, November 10, 1959.

Manuscript received by the Editor October 26, 1959.

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presence of a horizontal acceleration, the suspended meter is deflected by an angle, θ, with respect to the true vertical and so measures the vector sum of the true gravity plus vertical acceleration and the horizontal acceleration. The average of this vector sum is too great by an amount proportional to θ^2. This correction, first pointed out by Browne (1937) can be determined if θ can be measured, but this requires a gyroscopically stabilized platform or some other reference to the true vertical. Vening-Meinesz devised a horizontal bar on a knife edge and with a period of about one-half minute to evaluate this correction for pendulum gravity measurements. For the submarine gravity meter the horizontal acceleration meter uses, as a horizontal reference, a horizontal bar supported on ligaments with a period which can be made as long as five minutes but is usually operated with a one-minute period. Two perpendicular horizontal references are used to measure the longitudinal and transverse components of the angle of tilt as the meter swings in its gimbal support. The two components are squared, added, and smoothed to compute the Browne correction automatically. Simultaneous measurements in a submarine and with a Vening-Meinesz pendulum apparatus indicated that the meter has a precision comparable to that of the pendulum (Spiess and Brown, 1958).

The successful use of the gravity meter on a submarine led to further developments which permit still wider range of motion and which made possible gravity measurements on a surface ship (LaCoste, 1959; Harrison, 1959). When tests of a surface ship meter were described at the SEG meeting in San Antonio in October, 1958, the question was raised as to whether or not gravity could be measured in an airplane. The answer given at that time was that probably the instrument itself could be operated in an airplane, but there was a serious question as to whether the navigation of the plane would have the precision required to make the necessary corrections with useful accuracy.

The problem of making gravity measurements in an airplane is more difficult than on a surface ship because of the very large magnitude of the Eötvös effect, and also in an airplane, unlike on a surface ship, accurate control or measurement of elevation is required because of the free air gravity effect which amounts to about one mg for each 10 ft of change in elevation. Furthermore, changes in vertical velocity of the airplane must be measured to distinguish the resulting vertical accelerations from changes in gravity.

The first trial of a gravity meter in an aircraft was made in tests carried out by the U. S. Air Force, under the sponsorship of the Air Force Cambridge Research Center. A LaCoste surface ship gravity meter was carried in a KC-135 jet airplane with navigation by Doppler radar and barometric elevations. Horizontal and vertical positioning were checked with photo-theodolites on the Askania range near Edwards Air Force Base, California. This test indicated that significant gravity measurements could be made and that the over-all precision was about 10 mg (Thompson and LaCoste, 1960).

THE AIRBORNE GRAVITY METER

The meter used in the Air Force tests and in the tests described here is similar to the surface ship meter used on the "Hidalgo" (LaCoste, 1959). However, the reading system described there was not used because the airplane application demands very fast readings and a new reading system was devised.

The faster reading method can be described with the aid of Figure 1 which shows a simplified diagram of the gravity meter.

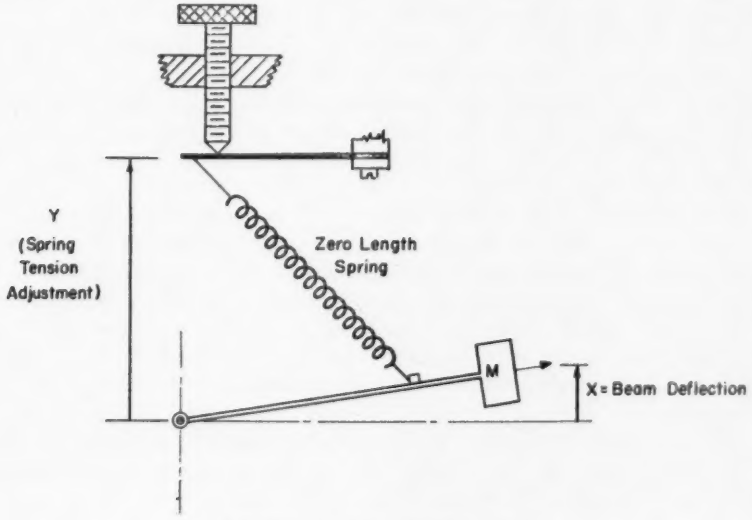
The equation of motion of the beam is:

$$\ddot{x} + R\dot{x} + kx = g + a + Ky,$$

where

x = deflection of the beam from zero position,
y = spring tension adjustment,
g = gravity,
a = acceleration of the meter as a whole.
R, k and K are empirical coefficients.

In a reading with a stationary meter, $a = 0$, and when the usual null adjustment is made, x and its time derivatives ($\dot{x}$ and $\ddot{x}$) are zero so that $g = -Ky$. If an operator does not have time to null the beam, he can let it come to rest, measure



Gravity Meter Diagram and Equation

FIG. 1. Principle of zero length spring gravity meter.

its deflection x, and make a corresponding correction. We will refer to this correction as a Displaced Beam Correction because it is due to the position of the beam and corrects for the term kx on the left side of the equation. But $\ddot{x}$ and $\dot{x}$ are still zero at the moment of reading because the beam has come to rest. The gravity reading is then equal to the sum of the spring tension adjustment plus the beam correction plus any acceleration correction.

In order to speed up the reading process even more, it is necessary to obtain readings before the beam has come to rest. To accomplish this, the whole of the left side of the differential equation must be evaluated. This is done by an analogue computer in the gravity meter, and the result is referred to as the Moving Beam Correction. With this new correction, it is still true that the gravity reading is equal to the sum of the spring tension adjustment plus the Moving Beam Correction plus accelerations. This new reading method is very important in airborne gravity work because readings must be obtained very quickly.

The time integral of the Moving Beam Correction (for flight line six of the tests described later) is shown by Curve A of Figure 2. The slope of this record is the Moving Beam Correction. The integral was used because of convenience in averaging. In order to filter out the short period variations (periods under one minute) in this record, it was filtered four times through a resistance-capacitance filter. The time lag due to filtering was eliminated by running the record through the filter forward twice and backward twice. The filtered or averaged integral of the Moving Beam Correction is Curve B of Figure 2.

Curve C of Figure 2 is the integral of the Spring Tension Adjustment (i.e., $\int Kydt$). As previously explained, the gravity reading is the sum of the Spring Tension Adjustment and the averaged Moving Beam Correction; therefore, the integral of the Gravity Reading should be the sum of the two lower curves in Figure 2. It is actually the difference (e.i., Curve C minus Curve B) because of the choice of signs.

This difference curve is shown by Curve A of Figure 3; actually Curve A also includes the vertical acceleration correction described below (Curve C of Figure 4). A slope of two divisions/minute on this curve corresponds to 50 mg. If slopes are averaged over one-minute intervals, the values denoted by x's along Curve B are obtained. These points represent the variation of gravity for flight line six. It can be seen that these values show a considerable scattering of readings. This scattering is a measure of the relatively short period vertical accelerations.

The open circles on Curve B in Figure 3 are obtained by averaging the slope of the upper curve over three-minute intervals. The scattering of these points is much less than that of the one-minute averages.

CORRECTIONS FOR AIRPLANE ACCELERATIONS

The operations discussed immediately above give a smoothed curve for the total acceleration measured in the airplane. It remains to make a correction for

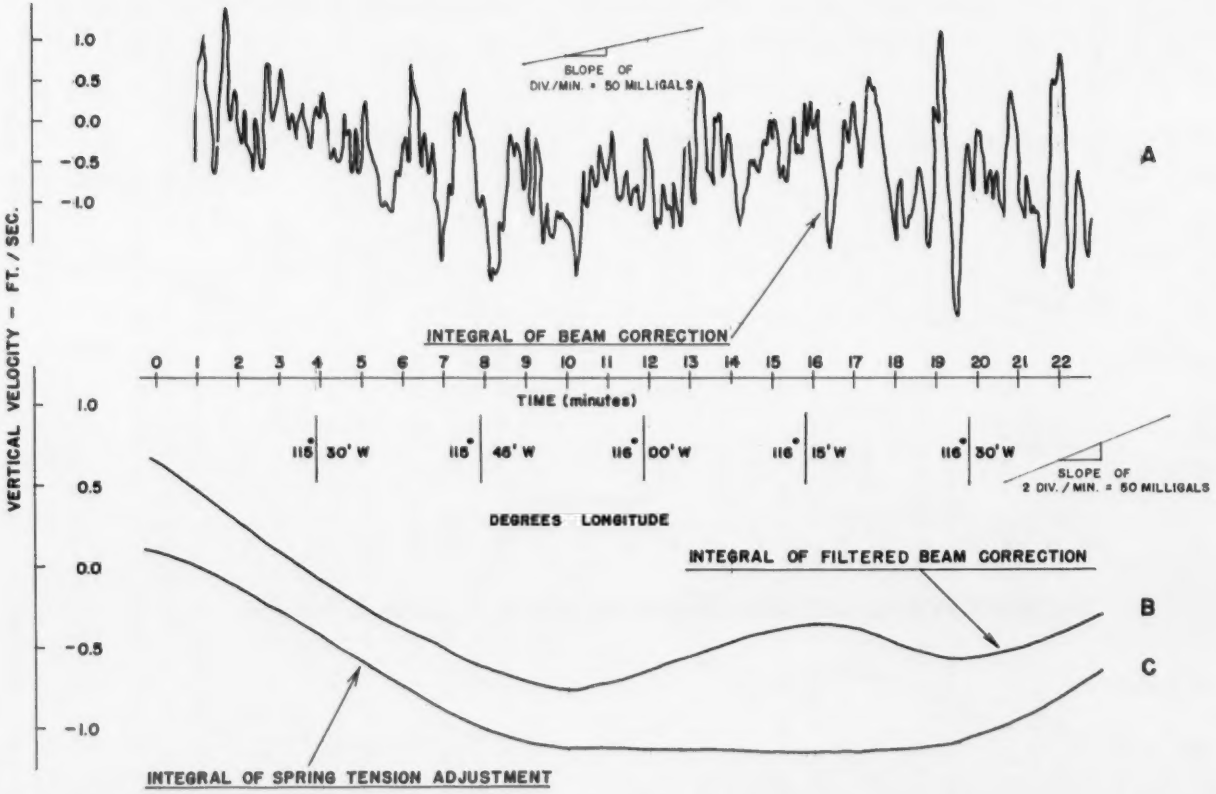


FIG. 2. Integral of moving beam correction for flight line 6; unfiltered record shown by Curve A; averaged integral shown by Curve B; integral of spring tension adjustment (i.e. $\int KY dt$) shown by Curve C. Note that vertical scale for Curves B and C is double that for Curve A.

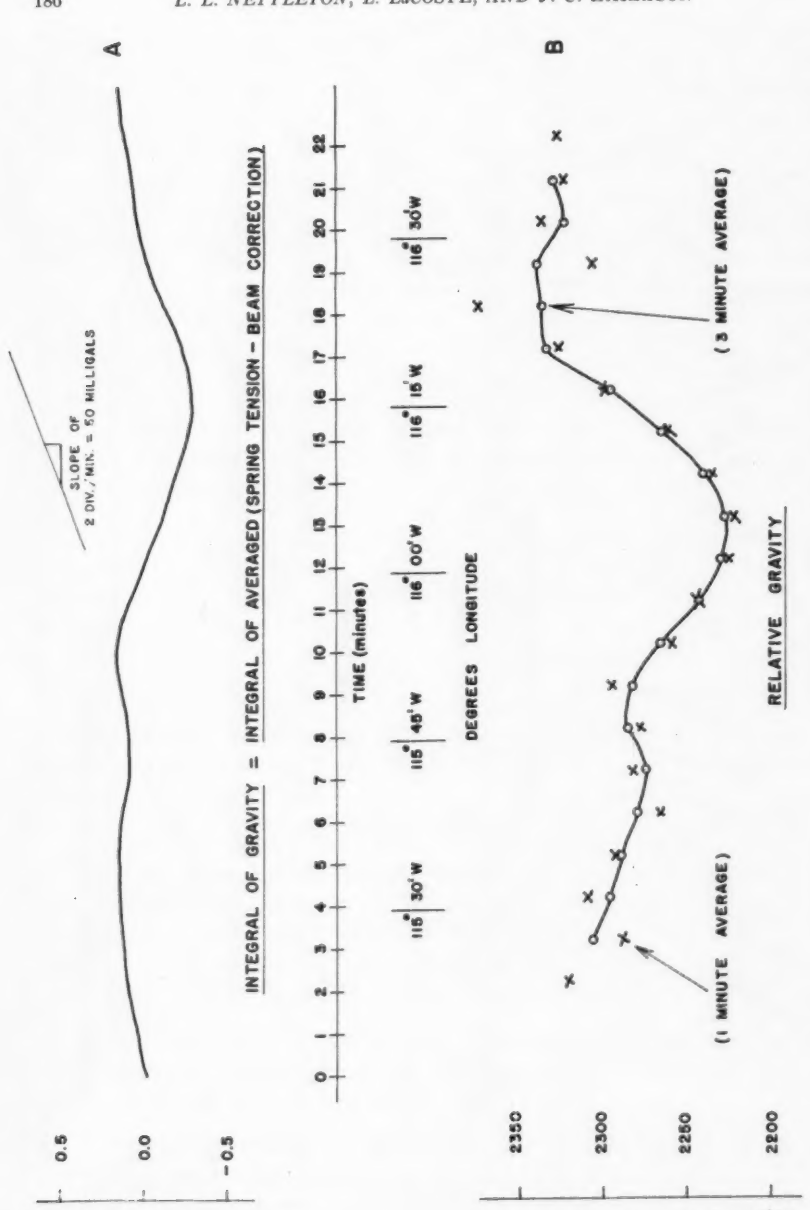


FIG. 3. Integral of gravity (Curve A) and relative gravity values (Curve B) from flight line 6.

the accelerations resulting from short period changes in height of the airplane and the correction for horizontal acceleration, corresponding to the Browne correction in pendulum measurements.

Vertical Acceleration Corrections

In order to determine the vertical accelerations of the airplane, a hypsometer was used. A hypsometer is a very accurate pressure altimeter which measures pressure by determining the boiling point of a liquid. It is capable of measuring changes in altitude to an accuracy of 2 ft.

The altitude record as determined by the hypsometer was filtered by the same filter which was used to filter the beam correction record; this filtering removes high frequencies. Curve A of Figure 4 shows the unfiltered hypsometer record for flight line six. The filtered record is shown by Curve B. This filtered record was then differentiated with respect to time to give Curve C, which is the integral of the vertical acceleration correction;[1] the differentiation was done by measuring the slope of the curve over three-minute intervals. Successive measurement of slope were made one minute apart. Curve C of Figure 4 is the previously mentioned integral of the vertical acceleration correction included in Curve A of Figure 3. Thus, Curve A of Figure 3 is Curve C of Figure 2 minus Curve B of Figure 2 minus Curve C of Figure 4.

Horizontal Acceleration Corrections

As mentioned previously, for surface ship measurements, the corrections for horizontal accelerations are ordinarily made automatically by a computer in the gravity meter. These accelerations are sensed by the previously mentioned pair of perpendicular balanced horizontal inertial bars with one-minute period which serve as stabilized references for measuring the longitudinal and transverse components of the angle of tilt of the gimbal-supported instrument. The corresponding components of the horizontal acceleration are proportional to the sum of the squares of these angles.

For surface ship measurements, an analogue computer ordinarily computes and adds the correction due to horizontal accelerations on the assumption that the periods of the horizontal accelerations are short compared to one minute. However, in an airplane the horizontal accelerations sometimes have periods longer than one minute, which require a more complicated computer. For this reason, the automatic computer was not used in this test, and, instead, records of the horizontal accelerations were made. The horizontal corrections were calculated later from these records. In future tests it is planned to increase the period of the stabilized reference system to two or three minutes and use the analogue computer.

[1] The hypsometer measures h (i.e., small changes in height of the airplane). The vertical acceleration is $d^2h/dt^2 = \ddot{h}$. The time derivative of the hypsometer record gives $\dot{h}$, which is the time integral of $\ddot{h}$.

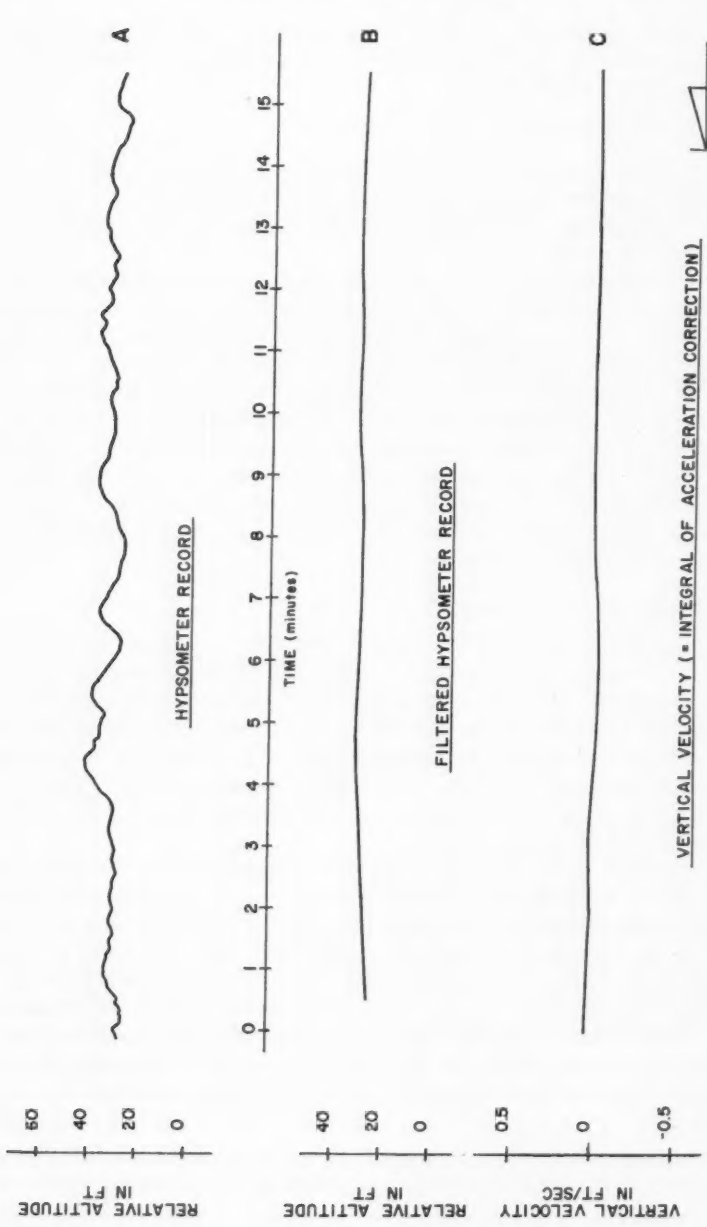


FIG. 4. Hypsometer record, unfiltered (Curve A) and filtered (Curve B) and integral of vertical acceleration correction (Curve C) for flight line 6.

Curves A and B of Figure five show the transverse horizontal accelerometer records for flights nine and five, respectively. The period of the accelerations is determined by the reaction of the automatic pilot to atmospheric disturbances. For flight five it can be seen that the periods of motion are under 20 seconds. With this short period, the horizontal correction can be accurately calculated from the record and flight line five gave very good results. However, for flight nine it can be seen that there are periods of about one to two minutes which have considerable amplitude. Therefore, a correction had to be made for these long periods. The correction was made by using the known response of the horizontal accelerations; the correction was estimated to be of the order of 100 mg. It should be noted that this correction cannot be considered to be very accurate because of the existence of more than one long period acceleration in the record. (In the final results line nine, flown when the atmosphere was becoming turbulent, was not satisfactory.)

The horizontal acceleration records for the longitudinal and transverse accelerometers were squared, smoothed, and the two correction components determined were added. The horizontal acceleration always increases the apparent gravity, and, therefore, the total horizontal acceleration correction is always subtracted from the total measured acceleration to give the averaged measured gravity value.

The general procedures of observation and reduction of the gravity meter data as outlined above were established from previous experience wtih surface ship observations together with that from the test flight made by the Air Force.

THE EÖTVÖS EFFECT

A gravity measurement on a moving platform modifies the normal centrifugal acceleration due to rotation of the earth. This effect was first pointed out by Baron von Eötvös (better known as the inventor of the torsion balance) in connection with the reduction of gravity measurements made at sea. For gravity measurements made in an airplane, the effect becomes much larger and imposes very stringent requirements on the navigation of the plane.

The normal centrifugal acceleration is proportional to the square of the speed of rotation of the earth. If the apparent velocity is changed by east or west motion of the gravity meter, there is a corresponding change in the outward (or upward) acceleration which will be increased by eastward motion and decreased by westward motion. Thus, the correction to the measured downward acceleration will be positive for eastward velocities and negative for westward velocities. At a speed of 200 mph, the correction is of the order of 1,000 mg. There is also a correction for the northward or southward component which corresponds to the motion over a non-rotating earth. This effect is much smaller because it is not linearly combined with the velocity due to the rotation of the earth. This north-south effect has been ignored in gravity measurements at sea until recently (Worzel, 1959) but becomes important in an airplane. For instance,

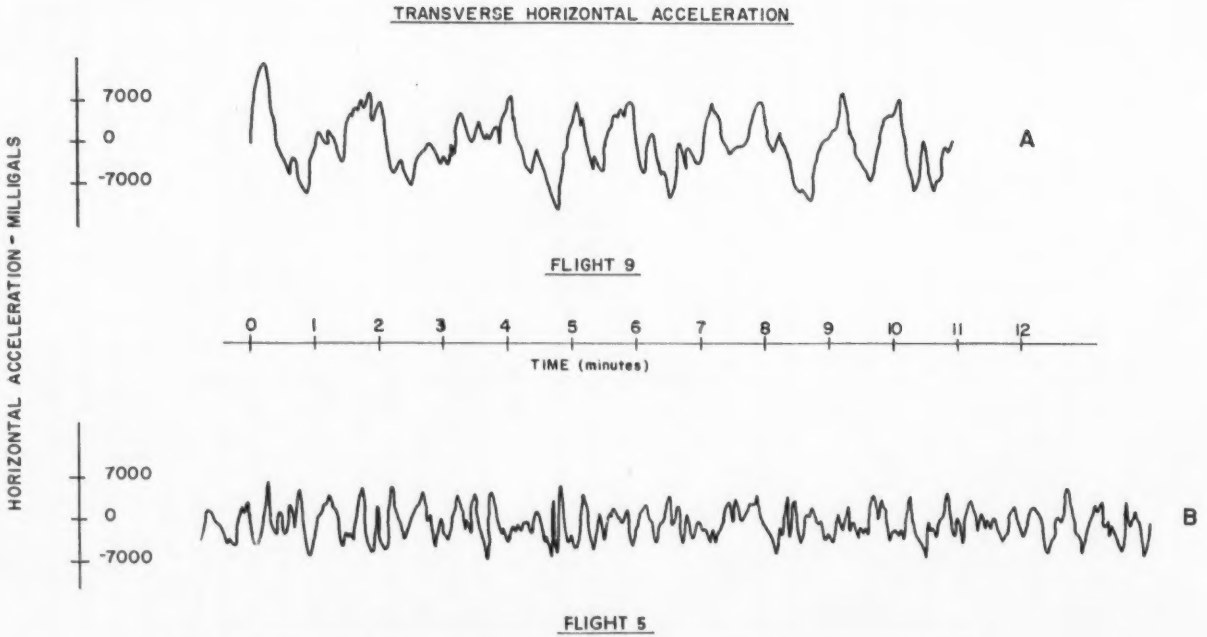
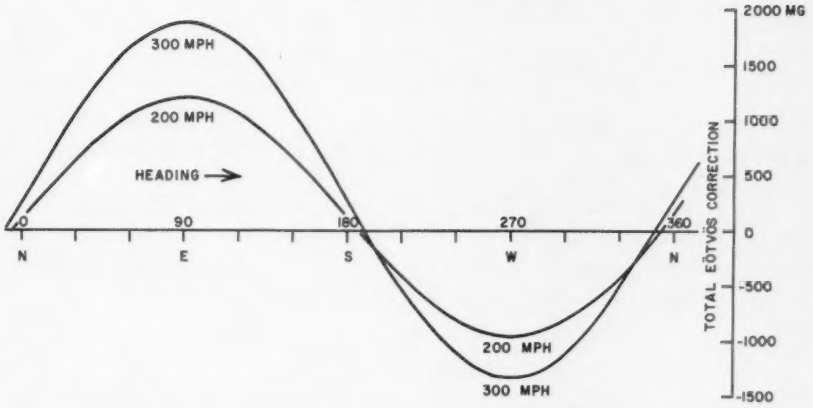


FIG. 5. Transverse horizontal acceleration records for flight line 9 (Curve A) and line 5 (Curve B).



VARIATION OF EÖTVÖS CORRECTION WITH CHANGE OF HEADING FOR LATITUDE 35°

FIG. 6. Variation of Eötvös Correction with heading, computed for speeds of 200 and 300 miles per hour at latitude 35°.

at 200 mph, this effect is about 175 mg. The total Eötvös correction, for speeds of 200 and 300 mph for flights in various headings, is shown by Figure 6.

The quantitative evaluation of the Eötvös correction is based on the following expression:

For an airplane at height h, moving with speed components V_n north (or south) and V_e east (or—V_e west) the Eötvös correction is given (Thompson and LaCoste, 1960) by:

$$E = \frac{R_\phi + h}{R_\phi^2}\left[(V_\phi + V_e)^2 + V_n^2 - V_\phi^2\right],$$

where

R_ϕ = radius of earth at latitude ϕ,
V_ϕ = speed of rotation of earth's surface at latitude ϕ,
$= R_\phi\ \omega \cos \phi$,
$V_e = V \cos \alpha$ where V is the grounds speed and α is the heading, and
$V_n = V \sin \alpha$.

The first term is the total centrifugal effect for the speed of rotation plus the east (or minus the west) component of motion. The second term is the effect of the north (or south) component of motion which is not affected by the rotation. The third term is the normal centrifugal effect for a point stationary with respect to the earth's surface and is subtracted to give the correction.

The expression may be written

$$E = \frac{R_\phi + h}{R_\phi^2}\left[2V_\phi V_e + V_e^2 + V_n^2\right] = \frac{R_\phi + h}{R_\phi^2}\left[2V_\phi V_e + V^2\right]$$

The factor $(R_\phi+h)/R_\phi$ makes a small correction for the fact that the height, h, is added to the effective radius of the earth. The term $2V_\phi V_e$ is plus or minus depending on whether V_e is east or west.[1]

This expression gives the Eötvös correction in cgs units of acceleration, i.e., gals or cm/sec^2, when distances are in centimeters and velocities in cm/sec. To change units, for instance to distances in miles and velocities in miles per hour, the unit of acceleration becomes mi/hr^2, and we must multiply by

$$\frac{1.60935 \times 10^5}{(3600)^2} = .0124178$$

to keep the result in gals. (The numerator is the number of centimeters in one mile; the denominator is the square of the number of seconds in one hour.)

The numerical calculation of Eötvös corrections may be illustrated by the following example:

Let us assume that the airplane is flying on a N 60°E course, or a 60° heading, at 200 mph, at elevation 13,200=2.5 mi and at latitude 35°.

The earth's radius changes with latitude corresponding to the flattening at

[1] The question has been raised as to the relation of the Eötvös correction to the Coriolis force. The Coriolis acceleration is defined as $2\ \boldsymbol{\omega}\times\mathbf{V}$, i.e., twice the vector product of the rotation vector (directed north along the earth's axis of rotation) times the velocity vector, **V**. The magnitude of this product is $2\,\omega V \sin\theta$, where θ is the angle between the vectors. The direction of the acceleration is perpendicular to the plane containing the $\boldsymbol{\omega}$ and **V** vectors.

The relation to the Eötvös effect can be clarified by considering separately the east and north components of **V**.

The plane containing $\boldsymbol{\omega}$ and the east component of **V** is parallel with the earth's axis, and the vertical component of this acceleration is $2\,\omega\, V_e \cos\phi$. But $r\,\omega\cos\phi = V_\phi$ and, therefore,

$$2\,\omega\, V_e \cos\phi = \frac{2\,V_\phi\, V_e \cos\phi}{r},$$

which is the first term of the Eötvös correction equation. Thus, the vertical component of the Coriolis acceleration is included in the Eötvös correction.

The plane containing $\boldsymbol{\omega}$ and the north component of **V** is vertical and, therefore, the Coriolis acceleration for this component is horizontal. For speeds of 200 mph, this component may amount to one gal (1,000 mg), which can be shown, as follows, to contribute a negligible amount to the quantity measured:

If we let G represent the vertical gravity, C the horizontal component of the Coriolis acceleration, then the measured value will be

$$G_m = \sqrt{G^2 + C^2} = G\sqrt{1 + \left(\frac{C}{G}\right)^2}, \qquad = G\left[1 + 1/2\left(\frac{C}{G}\right)^2\right].$$

Since C/G is of the order .001, the one gal horizontal effect would contribute only $\frac{1}{2}$ mg to the measured effect.

the poles and is given (Heiskanen and Vening-Meinesz, 1958) by $r = 6{,}378{,}388 \times (1 - .0033670 \sin^2 B + .0000071 \sin^2 2B)$ where B is the geographical latitude. This gives the radius in meters. For the radius in miles, the first coefficient is changed to 3963.33. From these values, the radius at latitude 35° is 6,371,362 meters or 3959.0 mi $= R_\phi$.

The speed at sea level due to the earth's rotation is $V_\phi = R_\phi \omega \cos \phi$. The angular rotation, $\omega = 2\pi/T = .000072921$ where T is 86164, the number of seconds in a sidereal day. These values give $V_\phi = 38058$ cm/sec $= 851.33$ mi/hr.

For a speed of 200 mph on the 60° heading, the east component is $200 \times \sin 60° = 173.2$ mi/hr. The north component is $200 \times \cos 60° = 100.0$ mi/hr.

We now put these various values in the equation for the Eötvös correction, using units of miles and miles per hour, and including the conversion factor for change of units, and have

$$E = .0124178 \times (3959.0 + 2.5) \left[\frac{2 \times 851.33 \times 173.2 + (173.2)^2 + (100)^2}{(3959.0)^2} \right],$$

$$= 49.1931 \left[\frac{294{,}901 + 29{,}998 + 10{,}000}{15.6738 \times 10^6} \right] = 1.051 \text{ gals} = 1051 \text{ mg}.$$

If the course were reversed, i.e., if the plane were flying S 60° W or on a 240° heading, the sign of the first term in the bracket would be reversed and the correction would be

$$E = 49.1931 \left[\frac{-294{,}901 + 29{,}998 + 10{,}000}{15.6738 \times 10^6} \right] = -.800 \text{ gals} = -800 \text{ mg}.$$

Because of the large value of the factor $2V_\phi$, the Eötvös correction is quite sensitive to any change in the east or west component of velocity. At intermediate latitudes, this factor makes a change of about 6 mg for a speed change of one mile per hour. At a speed of 200 mph eastward, the Eötvös correction is approximately 1,200 mg and for the same speed westward, it is approximately 1,000 mg. (See Figure 6) For a nearly north or south course, the total Eötvös correction is smaller (because V_e is small), but small changes in direction become very important, corresponding to the steep slopes of the curve of Figure 6 near courses of 180° or 360°. For instance, at a speed of 200 mph north, a change of course of one degree would introduce an east or west component of 3.5 mph which would introduce an acceleration of nearly 20 mg. Because of these large corrections, it is necessary that the speed and course of the plane be known with high precision.

TEST PROGRAM WITH COMMERCIAL EQUIPMENT

With the demonstration by the Air Force that gravity could be measured in the air with usable precision, it seemed worthwhile to carry out further experiments to determine whether or not satisfactory measurements could be made

with commercially available equipment and without the very special and elaborate navigation used in the Air Force tests.

The tests described below were carried out under a cooperative arrangement among Fairchild Aerial Surveys, Inc., who furnished the airplane and navigation equipment; LaCoste and Romberg, who had made the meter; the Institute of Geophysics at UCLA, who loaned a meter being used for surface ship measurements under sponsorship of the Office of Naval Research; and Gravity Meter Exploration Company, who planned the test, calculated the results, and compared them with surface measurements. The meter was operated by Lucien LaCoste and J. C. Harrison.

The tests were made with a converted B-17 airplane equipped with a six-inch aerial mapping camera, a 35 mm aerial spotting camera, and APR precision radar altimeter with the previously mentioned hypsometer for measuring small changes in elevation. The gravity meter used was similar to the one used on the "Hidalgo" (LaCoste, 1959). Changes in operating procedure, recording and auxiliary equipment were made to incorporate the special techniques required for airborne gravity measurement as outlined above.

The flights from which the data of this report were obtained were made on May 12, 1959, over and around the Imperial Valley of California. Observations were made between 7:35 and 11:50 A.M., when the air became too turbulent for satisfactory operation of the meter. Observations were made over a total of 490 miles of flight course, approximately 85 percent of which gave satisfactory results.

This test area was chosen because there are very large changes in Bouguer gravity (a minimum of some 80 mg over the valley) and the surface topography has several thousand feet of relief at the sides of the valley. The flat valley floor and the Salton Sea provided areas where precise elevation checks could be made with the radar altimeter. Furthermore, a fair network of ground gravity stations is available. The test lines were laid out with a number of intersections which would serve to check the results by comparison of values at points where the lines crossed.

For most of the test described here, the airplane was flown at a nominal elevation of 12,500 ft. The aircraft was operated on automatic pilot during all gravity measuring runs. During observations, recordings were made of:

(1) the integral of moving beam correction (see Figure 2, Curve A),
(2) the meter measuring screw position (spring tension adjustment),
(3) the transverse horizontal accelerometer (see Figure 5),
(4) the longitudinal horizontal accelerometer,
(5) the hypsometer reading (see Figure 4, Curve A),
(6) the radar altimeter reading.

Simultaneous index marks, controlled by the six-inch mapping camera, were made so that corresponding fiducial marks were registered on all the records

each time a picture was taken. The camera also recorded a clock face with sweep-second hand and a serial number so that for each picture a fiducial number and time were recorded by which all the individual records could be correlated with each other and with ground positions determined subsequently from the photographs. The time interval between pictures varied from about 15 to 30 seconds, depending primarily on the height above ground which changes the area covered by each photograph and the overlap.

DETERMINATION OF THE MAPPED VALUES

Because the instantaneous accelerations are very large, it is necessary that some averaging or smoothing procedure be used for calculating the gravity value as observed in the airplane. This was accomplished by the methods outlined above and illustrated in Figures 2, 3, and 4. These operations gave the smoothed gravity values in the airplane. It remained to determine the Eötvös and elevation corrections and the ground positions to construct a map of observed gravity at the average flight elevation. By far the largest and most troublesome correction is that for the Eötvös effect.

The location of the plane at the time of each fiducial mark was determined by matching the six-inch focal length aerial photographs with maps of the ground. USC & GS maps at scale 1:24,000 were used where available and maps at scale 1:62,500 for the remainder of the area. The Lambert coordinates were then determined for each such point. From these, the differences of x- and y-components (corresponding to north and east distances on the Lambert coordinate grid) were determined over approximately three-minute intervals. The time differences between the points at the ends of the interval were determined from the clock dial shown on the margin of each aerial photograph. From these distances and times the north-south and east-west components of speed were calculated. Since the Eötvös correction itself is a function of latitude, the values for the correction were made from a chart with curves for the east and west corrections for latitudes of 33° and 35° as a function of ground speed. The individual corrections were read off from this chart by interpolation between these two latitudes which bracket the entire area of the test. The north-south correction is read from a single curve as this is not modified by latitude or by the earth's rotation.

An example of the principal data involved in the gravity values and their corrections is given by Table 1. This table shows the elevation, speed and heading of the intersecting flights, the observed gravity (after corrections for vertical and horizontal acceleration) and the Eötvös corrections at the points of intersection, a free air correction to 12,000 ft elevation, the corrected gravity and, finally, the differences in the two measured values. It will be noted that, in spite of differences in Eötvös correction of as much as 2,000 mg (intersection of lines 6 and 5), the differences in the corrected values are generally in the range of plus or minus 10 mg or less.

TABLE I

Lines	Elevation above sea level (ft)	Speed (mph)	Heading	Observed Gravity (mg)*	Eötvös Correction (mg)	Elev. Corr. to 12,000 ft	Gravity gals†	Diff. (mg)
1	12,358	216	276.2°	2,249	−1,026	+34	978.449	
2	12,393	194	144.5	487	+ 723	+37	.439	+10
1	12,366	216	5.9°	2,235	−1,025	+34	.436	
5	12,411	198	127.7	231	+ 976	+39	.438	− 2
6	12,412	217	358.8°	2,231	−1,024	+39	.438	
2	12,392	192	145.0	488	+ 716	+36	.432	+ 6
6	12,415	217	359.4°	2,235	−1,021	+39	.445	
5	12,412	198	127.8	241	+ 973	+39	.445	0
6	12,412	217	358.8°	2,248	−1,029	+39	.450	
7	12,363	194	147.8	530	+ 681	+34	.437	+13

* On an arbitrary datum.
† On Potsdam datum through ground station at Burbank airport.

MAPPING THE AIRBORNE MEASUREMENTS

A free air gravity map at 12,000 ft from the airborne measurements is shown by Figure 7. The procedure for determining the values used to control this map is illustrated by Figure 8. On this figure, Curve A is the observed gravity in the airplane, corresponding to Curve B of Figure 3 (but plotted with west to the left while Figure 3 reads in accordance with the time sequence which is in the opposite direction). Curve B shows the individual Eötvös correction values, calculated as running averages at one-minute intervals over approximately three-minute or roughly ten-mile distance intervals. The scattering of these points must be due to small errors of timing or plotting ground positions and therefore, the smooth curve was used as the measure of the Eötvös correction. A free air correction was then added to bring the gravity to a uniform elevation of 12,000 ft, to give Curve C. The absolute value of the gravity scale for Curve C was established on the basis of a meter reading of 2,390 mg on the ground at the Lockheed Airport at Burbank and a gravity value, on the Potsdam datum, of 979.582 at the airport gate established by J. C. Rose of the Geology Department, University of Wisconsin. Curves similar to those of Figure 8 were made for all flight lines, and the map, Figure 7, was constructed from the values thus determined.

The comparisons with intersecting lines are indicated by the crosses which show the gravity values, at the points of intersection, from the lines which cross line 6. The departures of these points from Curve C correspond to the differences in the last column of Table 1. The circles represent gravity at 12,000 ft as calculated from ground stations under the flight line, as described in the next section.

A free air gravity map from ground readings over a somewhat broader area, including the area of the airborne map, is shown by Figure 9. The data for this map were furnished by Dr. G. P. Woollard of the University of Wisconsin. The values contoured are the free air gravity; i.e., the observed gravity on the Potsdam datum, with a free air correction to sea level. The general pattern of the gravity field is quite similar to that of the map from the airborne data.

COMPARISON WITH SURFACE GRAVITY

In comparing airborne with ground measurements, it is necessary to take into account the smoothing of the anomaly pattern at the height of the airplane owing to the increased distance from the masses causing the gravity variations. This smoothing or attenuation can be evaluated by upward continuation as discussed by Peters (1949), Henderson and Zietz (1949), and others. The smoother field at a higher level is calculated by means of a set of coefficients operating on a grid of values at the level of the observed field.

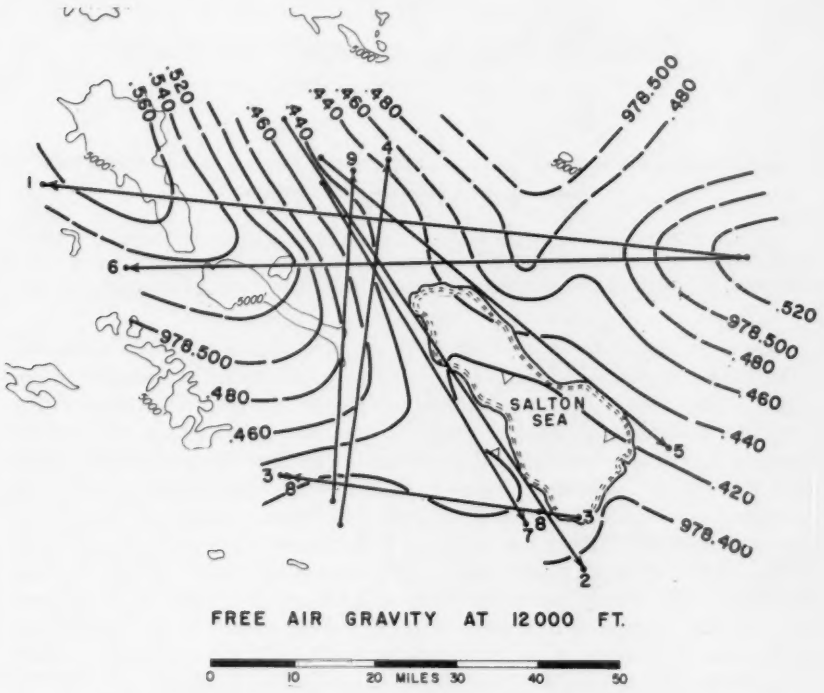


FIG. 7. Free Air Gravity at 12,000 ft from airborne observations. Areas of high topography indicated by 5,000 ft elevation contours.

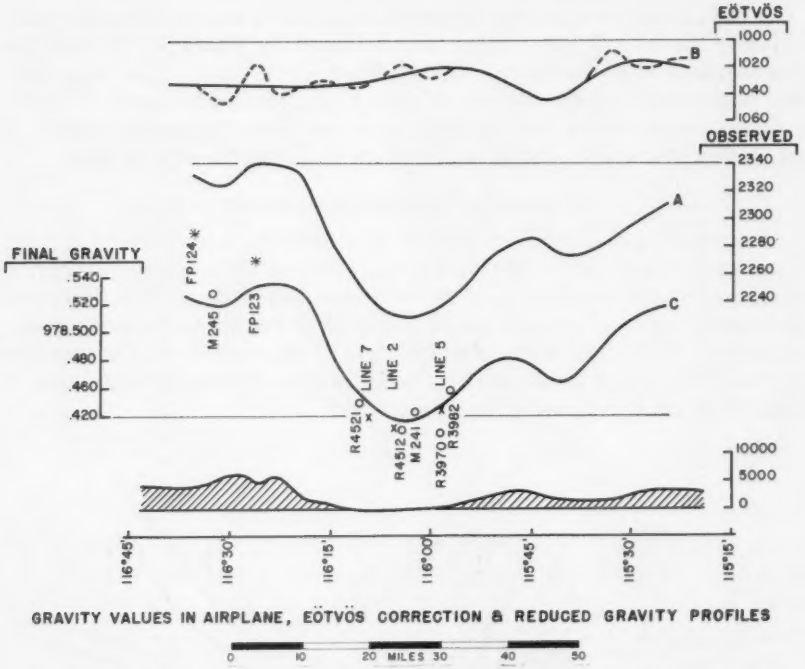


FIG. 8. Profiles of observed gravity in airplane (Curve A), Eötvös correction (Curve B), and final gravity (Curve C) for flight line 6. Final values from intersecting lines shown by *X*'s. Values calculated from ground stations shown by circles. Topography under flight line shown at bottom.

The ground gravity map (Figure 9) shows a strong minimum over the Imperial Valley which is sharp enough to be considerably attenuated at the height of the airplane. The continuation calculation was made to determine this attenuation. A two-mile grid of gravity values was written from the free air anomaly map. Peters' coefficients, computed for $1\frac{1}{4}$ times the grid spacing, were used to calculate the continued gravity at $2\frac{1}{2}$ miles, which is approximately the average flight elevation. Curve A of Figure 10 shows a profile of the free air anomaly at sea level along the course of flight line 6. The continued gravity is shown by Curve B. The flattening, or attenuation, decreases the depth of the minimum in the central part of the profile and reduces the heights of the maxima on the flanks. This gives a positive "attenuation correction" in the central part of the area and a negative correction on the flanks, as shown by Curve C which is the difference between the other two. The topography along the line is shown at the bottom of the figure.

To calculate gravity at the height of the airborne observation, we subtract

from the surface station value the free air effect for the difference in elevation between the ground station and the height of the airborne observation and add or subtract the "attenuation correction" as determined from the continuation calculation. This was done to give the calculated points as shown along Curve C of Figure 8. A similar calculation was made from all ground stations near the usable flight lines to give the results shown by Table II. For part of the stations listed, indicated by **, the attenuation calculations were not made because of inadequate ground control.

The airborne gravity measurements are averages. This fact has little effect on a line along which gravity variations are small but tends to smooth out features within the three-minute (or roughly ten-mile) averaging interval. This effect means that perfect agreement at flight line intersections is not necessarily to be expected, and it also complicates the evaluation of comparisons with ground data.

EFFECTS OF TOPOGRAPHY

It is beyond the scope of this report to attempt an analysis of the effects of

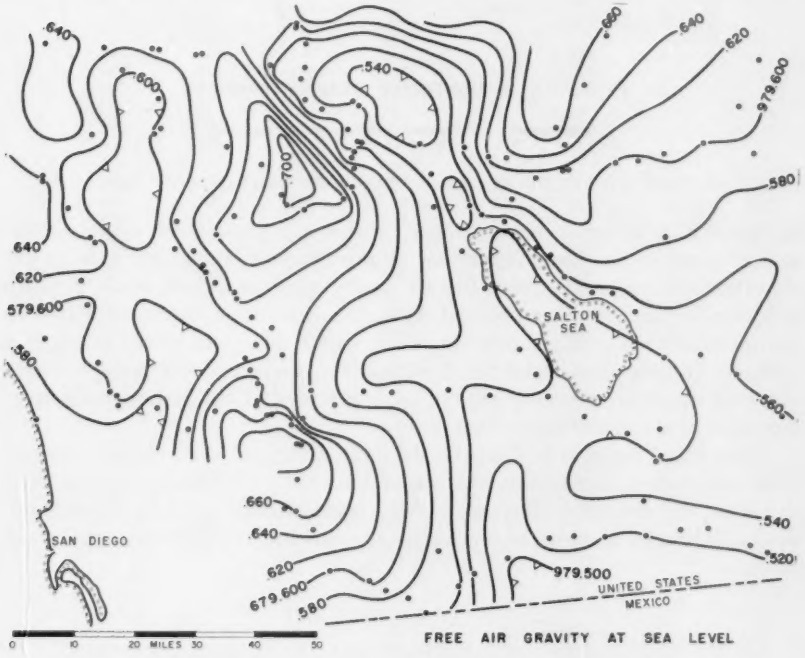


FIG. 9. Free air gravity at sea level from surface gravity observations (original data courtesy Prof. George P. Wollard, University of Wisconsin).

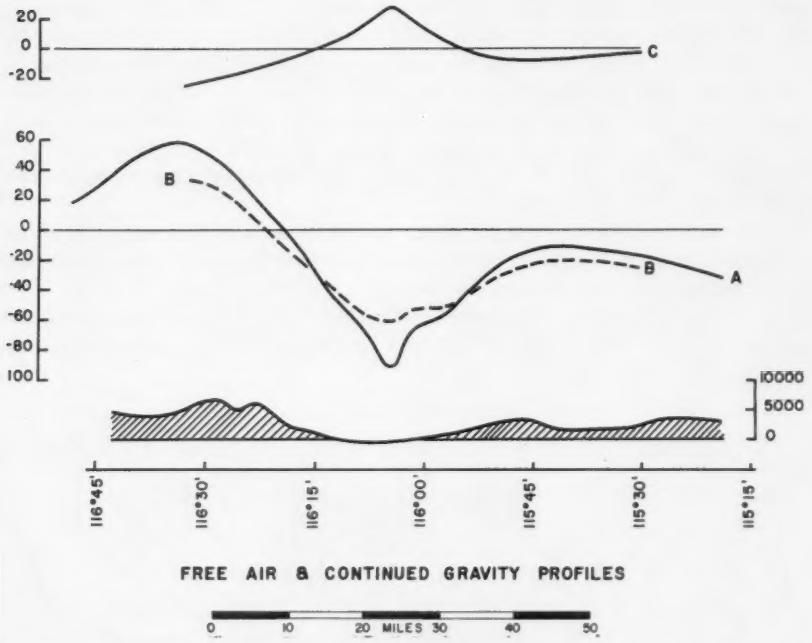


FIG. 10. Profile of free air gravity, continued gravity, and topography under flight line 6.

topography on airborne measurements. This would involve the degree of isostatic compensation, the attenuation of the Bouguer attraction with height above the surface, etc. If simple free air gravity were used, there would be sharp anomalies in rugged topography and the attenuation correction, as calculated by continuation from widely scattered control, would miss much of the detail. It is probably because of effects of this kind that the comparisons of calculated with observed values are generally good in areas of low relief but become much more divergent in the more rugged areas.

From the differences in Table II, the mean difference of all values computed with attenuation corrections, and where elevations are less than 1,500 ft, is −3.4 mg, and the mean difference without regard to sign is 7.6 mg. For the few available ground stations in the higher topography, the differences are much larger.

CONCLUSION

On the whole, the test results indicate that gravity measurements in the air can be made to about 10 mg or better and that reliable maps can be constructed from airborne observations. The operation should be improved considerably by

TABLE II

COMPARISON OF GRAVITY VALUES FROM AIRBORNE OBSERVATIONS WITH VALUES COMPUTED FROM GROUND STATIONS

Flight Line	Station	Observed Gravity	Elevation	Free Air Gravity at Sea Level	Attenuation* Correction	Calculated Gravity at 12,000 ft	Observed Gravity at 12,000 ft	Difference Calculated-observed
1	N1122	979.463	1,499	979.604	+ 6	978.481	.485	− 4
	R3983	.514	1,080	.616	− 9	.478	.480	− 2
	R3982	.540	493	.586	− 3	.454	.464	−10
	R4520	.545	83	.553	+12	.436	.443	− 7
	M244	.402	2,448	.632	−10	.493	.505	−12
	FP121	.481	1,346	.607	**	(.478)	.509	−(31)
	M247	.281	4,150	.671	−10	.532	.567	−35
	M248	.354	2,946	.631	**	(.502)	.565	−(63)
3 & 8†								
3	R3974	.553	−179	.536	+ 1	.408	.410	− 2
8	R3974	.553	−179	.536	+ 1	.408	.416	− 8
3	R4502	.529	15	.530	+ 8	.409	.403	+ 6
8	R4502	.529	15	.530	+ 8	.409	.418	− 9
3	R4503	.532	163	.548	+ 5	.424	.406	+18
8	R4503	.532	163	.548	+ 5	.424	.423	+ 1
8	R4504	.481	992	.574	−16	.429	.420	+ 9
5	M242	.537	24	.539	+23	.433	.432	+ 1
	R4520	.545	83	.553	+12	.436	.434	+ 2
	R4512	.548	−189	.530	+28	.429	.439	−10
	M241	.565	− 50	.560	+12	.443	.440	+ 3
	R3970	.561	−195	.543	+15	.429	.445	−16
	R3971	.572	−196	.554	+ 6	.431	.450	−19
	M240	.580	−139	.567	− 3	.435	.448	−13
	R3972	.576	−188	.558	0	.429	.439	−10
	R3969	.576	−199	.557	+ 1	.429	.437	− 8
	M239	.560	− 75	.554	+ 5	.430	.436	− 6
	R3980	.572	−200	.553	+ 5	.429	.434	− 5
6 & 1-B‡								
6	R3982	.540	493	.586	− 3	.454	.452	+ 2
1-B	R3982	.540	493	.586	− 3	.454	.427	+27
6	R3970	.561	−195	.543	+15	.429	.446	−17
1-B	R3970	.561	−195	.543	+15	.429	.424	+ 5
6	M241	.565	− 50	.560	+12	.443	.438	+ 5
1-B	M241	.565	− 50	.560	+12	.443	.426	+17
6	R4512	.548	−189	.530	+28	.429	.437	− 8
1-B	R4512	.548	−189	.530	+28	.429	.429	0
6	R4521	.557	88	.565	+11	.447	.456	− 9
6 & 1-B‡								
1-B	R4521	979.557	88	979.565	+11	978.447	.456	− 9
6	FP123	.315	3,887	.680	**	(.551)	.535	+(16)
1-B	FP123	.315	3,887	.680	**	(.551)	.536	+15
6	M245	.270	4,351	.679	−22	.528	.519	+ 9
1-B	M245	.270	4,351	.679	−22	.528	.543	−15
6	FP124	.252	4,779	.701	**	(.572)	.522	+(50)
1-B	FP124	.252	4,779	.701	**	(.572)	.539	+33
1-B	FP125	.321	3,635	.663	**	(.534)	.528	+ 6
1-B	FP126	.328	3,542	.660	**	(.531)	.540	−(9)
1-B	R4532	.430	2,095	.627	**	(.498)	.504	−(6)
1-B	M252	.522	1,003	.616	**	(.487)	.502	−(31)
7	R4521	.557	88	.565	+11	.447	.441	+ 6
	R4522	.567	−140	.554	+ 7	.432	.433	− 1
	R4523	.563	−183	.546	+ 8	.425	.423	+ 2
	R3981	.558	−123	.546	− 3	.414	.422	− 8
	R3973	.548	− 10	.549	− 3	.417	.424	− 7
	R3974	.553	−179	.536	+ 1	.408	.434	−22

* Attenuation correction calculated by Peters' coefficients for 1¼ unit spacing from two-mile grid of free air anomaly values from ground data.

** Attenuation correction not calculated because ground data inadequate.

† Lines 3 and 8, flown 12 May, 1959, are coincident.

‡ Line 1-B, flown 8 May, 1959, is almost coincident with line 6, Fown 12 May, 1959, but extends 30 miles farther west.

use of Doppler navigation, which would give more precise data on course and speed, and should improve the precision of the Eötvös corrections. Some improvements in methods of recording the data from the meter are contemplated.

An airborne survey can give results quite adequate for geodetic purposes, for which smooth or average gravity over relatively large areas is required. It cannot take the place of a detailed ground gravity survey as, quite obviously, local features are greatly attenuated at the relatively great heights required for air smooth enough for airborne observations. The necessity of averaging the observations over an appreciable time contributes to further loss of detail. On the other hand, such surveys would be quite useful for broad reconnaissance where large features related to regional structure are present. For example, an airborne survey almost certainly would develop the large gravity anomalies associated with the Central Basin Platform in West Texas and New Mexico or the buried Amarillo Mountains and Anadarko basin of Oklahoma and the Texas Panhandle. It is estimated that an airborne gravity survey would have detail approximately equivalent to that which would be supplied by a grid of gravity stations on the ground at five-mile intervals.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 203–225, 6 FIGS.

RAPID COMPUTATION OF GRAVITATIONAL ATTRACTION OF THREE-DIMENSIONAL BODIES OF ARBITRARY SHAPE*

MANIK TALWANI† AND MAURICE EWING†

ABSTRACT

An expression is derived for the gravity anomaly at an external point caused by a horizontal lamina with the boundary of an irregular polygon. This expression is put in a form suitable for computation by a high speed digital computer. By making the number of sides of the polygon sufficiently large, any irregular outline can be closely approximated. Any three dimensional body can be represented by contours. By replacing each contour by a polygonal lamina, the anomaly caused by it can be obtained at any external point. By a system of interpolation between contours combined with a numerical integration the gravity anomaly caused by the three-dimensional body can be calculated to a high degree of precision.

This method may also be used for rapidly computing terrain corrections on a flat earth. By making a small modification it can further be adopted for computing the terrain correction as well as local isostatic compensation on the Airy system up to the external radius of Hayford zone *O* on a spherical earth.

The expression for the anomaly caused by a horizontal polygonal lamina is also obtained for the special case when the sides of the polygon are alternately parallel to the *x*- and *y*-axes, that is, the polygonal lamina can be divided into a number of rectangular laminae. A chart is provided for the hand computation of the gravity anomaly in this case.

INTRODUCTION

It is in general not possible to obtain an analytical expression for the gravity anomaly caused by an irregularly shaped three-dimensional body.

Most of the existing methods involve the use of graticules or mechanical integrators. The problem, fundamentally, is one of a triple integration and the various methods differ in the order in which the integrations are performed or in the choice of the coordinates used. Breyer (1939) discusses the relative merits of using different coordinate systems and also reviews the work of other authors who have constructed graticules based on these systems. Later authors including Gassmann (1951) and Baranov (1953) give methods, again involving the use of graticules but differing in the order in which the integration is performed. While in particular instances these methods may be highly suitable, the problem of scaling and difficulties in maintaining precision, inherent in all graphical methods, put a limit to their usefulness.

Ansel (1936, 1939) and Levine (1941) attack the problem by determining the effects of three-dimensional bodies of simple geometrical form. In theory by using a large number of such bodies, any irregularly shaped one can be approximated and its attraction determined. In practice, though, this may be very tedious if not inaccurate.

Nettleton (1940, 1942) gives two simple methods for making approximate

* Presented at the twenty ninth International Meeting, November 10, 1959. Manuscript received by the Editor June 12, 1959.

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calculations. One involves the use of circular discs and the other applies an "end-correction" to two-dimensional bodies. These methods have proved very useful for making a rough estimation of the attraction of three-dimensional bodies. When great precision is required, as in certain mining problems, these methods cannot be used.

The analytical problem becomes vastly simpler if one of the dimensions of the three-dimensional body becomes either infinite or infinitesimal. The latter case implies that the body has a laminar shape. One way of finding the anomaly caused by a three-dimensional body is to divide it into a large number of thin laminae, determine the anomaly for each and then add them up. For this method to be precise two conditions must be satisfied. Firstly, the double integration which gives the anomaly caused by the individual laminae must be accurate. Secondly, the laminae must be very thin in order that the final summation accurately represents an integration.

There is no restriction to the orientation of the laminae. Horizontal laminae have the advantage that they can be outlined by contours and have been used for this reason by several authors. Siegert (1942), for instance, describes the use of a mechanical integrator for such laminae. Nettleton (1942) has evaluated the anomalies caused by horizontal circular laminae by making use of the well-known fact that the anomaly due to any horizontal lamina is directly proportional to the solid angle it subtends at the point at which the anomaly is being evaluated. His results, however, can be used for only those bodies whose cross-sections approximate circles fairly well.

THEORY OF METHOD

In the present method the three-dimensional body is first represented by contours. Each contour is then replaced by a horizontal irregular n-sided polygonal lamina. By making the number of sides n sufficiently large, the polygons can be made to approximate the contour lines as closely as desired. The gravity anomaly caused by each lamina can be determined analytically at any external point and is plotted as a function of the height of the lamina (i.e. the contour elevation). By interpolation a continuous curve can be obtained relating the heights of the laminae with their gravity anomalies. The total area under this curve gives the gravity anomaly caused by the entire body and can be obtained either graphically or by numerical integration.

In Figure 1, P, the point at which the gravity anomaly caused by the massive body M is being evaluated, is chosen as the origin of a left handed cartesian coordinate system with the z-axis positive vertically downwards. A contour on the surface of the body at depth z below P is replaced by the polygonal lamina $ABCDEF \cdots$ of infinitesimal thickness dz. Let the gravity anomaly (that is, the vertical component of the gravitational attraction) caused by $ABCDEF \cdots$ at P, be termed Δg.

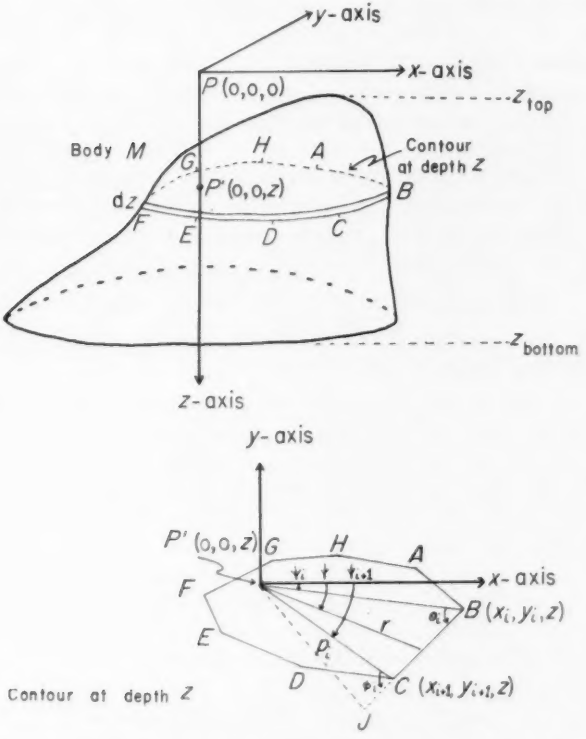

FIG. 1. Geometrical elements involved in the computation of the gravity anomaly caused by a three-dimensional body.

Then

$$\Delta g = V dz, \tag{1}$$

where V is the anomaly caused by $ABCDEF \cdots$ per unit thickness. Now V is expressed by a surface integral, the integration being carried over the surface of $ABCDEF \cdots$. This can be reduced to two line integrals, both along the boundary of $ABCDEF \cdots$, V being given by the expression

$$V = k\rho\left[\oint d\psi - \oint z/(r^2 + z^2)^{1/2} d\psi\right], \tag{2}$$

(the line integrals being evaluated along the boundary $ABCDEF \cdots$), where k is the universal constant of gravitation, ρ is the volume density of the lamina

and z, ψ and r are the cylindrical coordinates used to define the boundary of $ABCDEF \cdots$.

Let P' be the projection of P on the plane $ABCDEF \cdots$ (Figure 1). Then $PP' = z$, r is the radius vector in the plane $ABCDEF \cdots$ and ψ is the angle which it makes with an arbitrary x-axis in this plane. (ψ is taken positive in a clockwise sense from the positive x-axis).

Let us evaluate the contribution to the two line integrals from, say, side BC of the polygon. Proceeding in clockwise sense, the first integral yields the value $\psi_{i+1} - \psi_i$ on inspection, where ψ_{i+1} and ψ_i are the angles which the positive x-axis makes with $\overrightarrow{P'C}$ and $\overrightarrow{P'B}$, respectively. The second integral may be evaluated by drawing $P'J$ perpendicular from P' to BC. Let $P'J = p_i$. Also let θ_i and ϕ_i be respectively the angles which $\overrightarrow{BP'}$ and $\overrightarrow{CP'}$ make with $\overrightarrow{BC}$ (or $\overrightarrow{CB}$ if $\psi_{i+1} < \psi_i$). It is obvious from Figure 1 that

$$r = \frac{p_i}{\sin(\phi_i - \psi_{i+1} + \psi)} . \tag{3}$$

Making this substitution, and noting that p_i, ϕ_i and ψ_{i+1} are all constants, so that ψ is the only variable left, the integral can be easily solved for the segment BC to give the value:

$$\arcsin \frac{z \cos \theta_i}{(p_i^2 + z^2)^{1/2}} - \arcsin \frac{z \cos \phi_i}{(p_i^2 + z^2)^{1/2}} . \tag{4}$$

Thus the total contribution to V from BC is

$$k\rho \left[\psi_{i+1} - \psi_i - \arcsin \frac{z \cos \theta_i}{(p_i^2 + z^2)^{1/2}} + \arcsin \frac{z \cos \phi_i}{(p_i^2 + z^2)^{1/2}} \right]. \tag{5}$$

Expression (5) can be readily identified as the anomaly caused by the triangular lamina $P'BC$ per unit thickness at the point P. (See, for example, Ramsey, 1940, p. 44). This gives us some physical insight into the mechanism of the line integral. The gravity anomaly caused by the whole polygon $ABCDEF \cdots$ per unit thickness is obtained, then, by summing up expression (5) over the n sides of the polygon to obtain

$$V = k\rho \left[\sum_{i=1}^{n} \left\{ \psi_{i+1} - \psi_i - \arcsin \frac{z \cos \theta_i}{(p_i^2 + z^2)^{1/2}} + \arcsin \frac{z \cos \phi_i}{(p_i^2 + z^2)^{1/2}} \right\} \right]. \tag{6}$$

Noting that p_i, ψ_i, ψ_{i+1}, $\cos \theta_i$ and $\cos \phi_i$ can all be expressed in terms of x_i, y_i, the coordinates of B, and x_{i+1}, y_{i+1}, the coordinates of C, we see that V can be expressed exclusively in terms of the coordinates of the vertices of the polygon $ABCDEF \cdots$. We note in passing that

$$\sum_{i=1}^{n} (\psi_{i+1} - \psi_i) = 2\pi$$

when P' lies within the polygon but vanishes when P' lies outside it. In the particular case when it lies on the boundary of the polygon, its value equals the angle subtended at this point by the adjacent parts of the polygon boundary.

Hand computations can be easily made from equation (6) for laminae with up to five or six sides. For a larger number of sides, the computations become tedious; however, being iterative, they can be readily programmed for solution by a high speed digital computer. This is discussed at length later.

So far we have concerned ourselves with the anomaly caused by the lamina $ABCDEF \cdots$. The total anomaly Δg caused by the entire body M can be evaluated by integrating (1) between z_{top} and z_{bottom}, the vertical limits of the massive body M.

Thus

$$\Delta g_{\text{total}} = \int_{z_{\text{bottom}}}^{z_{\text{top}}} V dz. \tag{7}$$

V, of course, is obtained from (6). Except for a few elementary cases, this integral does not yield an analytical solution in a closed form. But it can be readily solved either graphically or by numerical integration. In either case V is determined from (6) for a number of contours. To solve the integral graphically, V is plotted against z, the depth of the contour and a smooth curve is drawn through these points. The area included between this curve and the axis representing z gives the value of the integral and can be measured simply by a planimeter or by using graph paper. A more objective solution can be obtained by numerical quadrature. A good approximation can be made, for instance, by fitting parabolas to sets of three points on the (V, z) plot and obtaining the area by simple analytical integration. This method, of course, reduces to Simpson's rule when the contour spacing is equal. Obviously, the closer the contours are spaced, the more accurate the determination of the anomaly. In a number of actual cases, as for example the evaluation of terrain correction from a given map, the contour interval is specified beforehand. This, of course, sets a limit on the accuracy attainable. On the other hand, for bodies whose configurations are precisely known the contours can be spaced as closely as desired. This is especially applicable to bodies of simple geometrical shape like the prism, the cylinder or the cone. For such bodies the accuracy of the determination of the anomaly can be further improved by using the more accurate Gauss' quadrature formula, which would require the contours to be spaced at certain unequal but specified intervals. (Details on Gauss' quadrature formula are given in any textbook on numerical integration. See, for example, Hildebrand, 1956, p. 319.)

The possibility that density varies with depth may be easily incorporated into the solution by assigning a separate density to each contour.

USE OF DIGITAL COMPUTERS

Programming

Modern high speed digital computers are well suited for evaluating the anomaly caused by each lamina from (6) and also for carrying out the numerical

integration (7) for determining the anomaly caused by the entire body. Actually both calculations can be handled by a single program. The input data describe the height and configuration of the contours which define the body and the output from the computer gives the anomaly for the body determined at any given number of external points.

To express V, the gravity anomaly caused by the polygonal lamina per unit thickness, in a form suitable for actual programming, equation (6) is expressed in terms of x_i, y_i, z and x_{i+1}, y_{i+1}, z, the coordinates of two successive vertices of the polygon. We can then rewrite (6) as

$$V = k\rho \sum_{i=1}^{n} \Big[W \arccos \{ (x_i/r_i)(x_{i+1}/r_{i+1}) + (y_i/r_i)(y_{i+1}/r_{i+1}) \} - \arcsin \frac{zq_iS}{(p_i^2 + z^2)^{1/2}} + \arcsin \frac{zf_iS}{(p_i^2 + z^2)^{1/2}} \Big], \tag{8}$$

where

$$S = +1 \text{ if } p_i \text{ is positive}, \quad S = -1 \text{ if } p_i \text{ is negative},$$

$$W = +1 \text{ if } m_i \text{ is positive}, \quad W = -1 \text{ if } m_i \text{ is negative},$$

$$p_i = \frac{y_i - y_{i+1}}{r_{i,i+1}} x_i - \frac{x_i - x_{i+1}}{r_{i,i+1}} y_i,$$

$$q_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \cdot \frac{x_i}{r_i} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \cdot \frac{y_i}{r_i},$$

$$f_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \cdot \frac{x_{i+1}}{r_{i+1}} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \cdot \frac{y_{i+1}}{r_{i+1}},$$

$$m_i = (y_i/r_i)(x_{i+1}/r_{i+1}) - (y_{i+1}/r_{i+1})(x_i/r_i),$$

$$r_i = + (x_i^2 + y_i^2)^{1/2},$$

$$r_{i+1} = + (x_{i+1}^2 + y_{i+1}^2)^{1/2},$$

$$r_{i,i+1} = + [(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2]^{1/2}.$$

The digital computer obtains the values of V for each contour from (8) and then solves (7) numerically to get Δg_{total}, the gravity anomaly caused by the entire body. As discussed earlier a convenient way to perform the numerical quadrature involved is to fit parabolas to successive sets of three points (obtained by plotting V against z) and then to find the area contained between the parabolas and the z-axis. If V_0, V_1, and V_2 are the values of V corresponding respectively to contours at heights z_0, z_1, and z_2, then the gravity anomaly caused by the portion of the body lying between horizontal planes at depths z_0 and z_2 is given by

$$\int_{z_0}^{z_2} V dz = \frac{1}{6}\left[V_0 \frac{z_0 - z_2}{z_0 - z_1}(3z_1 - z_2 - 2z_0) + V_1 \frac{(z_0 - z_2)^2}{(z_1 - z_2)(z_1 - z_0)} + V_2 \frac{z_0 - z_2}{z_2 - z_1}(3z_1 - z_0 - 2z_2)\right]. \quad (9)$$

We note that when the contours are equally spaced, that is, $z_0 - z_1 = z_1 - z_2$, (9) can be identified with a term from Simpson's rule. By choosing successive sets of three points, the quadrature can be carried out throughout the entire range (from z_{bottom} to z_{top}) and Δg_{total} obtained.

A program involving the use of equations (8) and (9) has been written for the IBM 650. If a three-dimensional body is represented by m contours and each contour is replaced by an n-sided polygon, the actual running time on the IBM 650 for the evaluation of the gravity anomaly due to this body at an external point is about $4mn$ seconds. A higher speed computer, for example the IBM 704, would require one-fiftieth of this time for doing the same problem.

Example

This method is demonstrated by the following example in which the gravity anomaly caused by the massive body M (Figure 2) is evaluated at a point P. This body is the same as chosen by Gassmann (1951) to demonstrate the evaluation of gravity anomalies by his method. The scale is the same as in Gassmann's publication and the contours which define the body are also identical with Gassmann's.

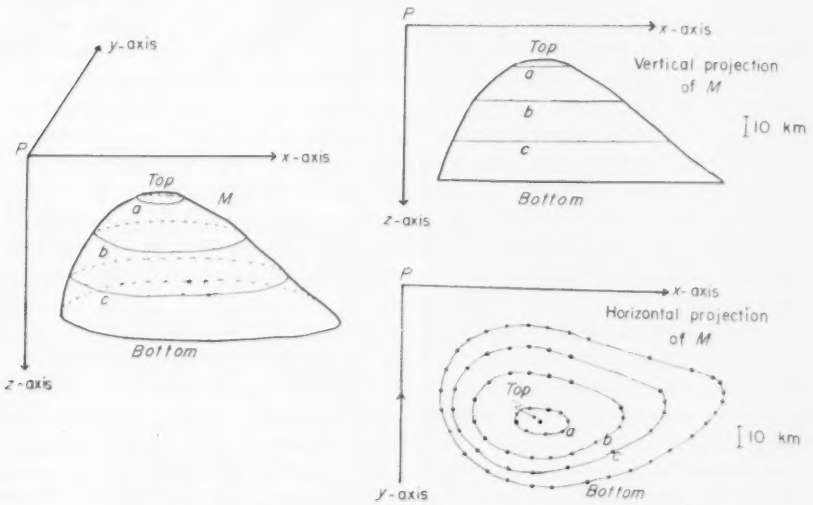

FIG. 2. Three-dimensional body represented by contours.

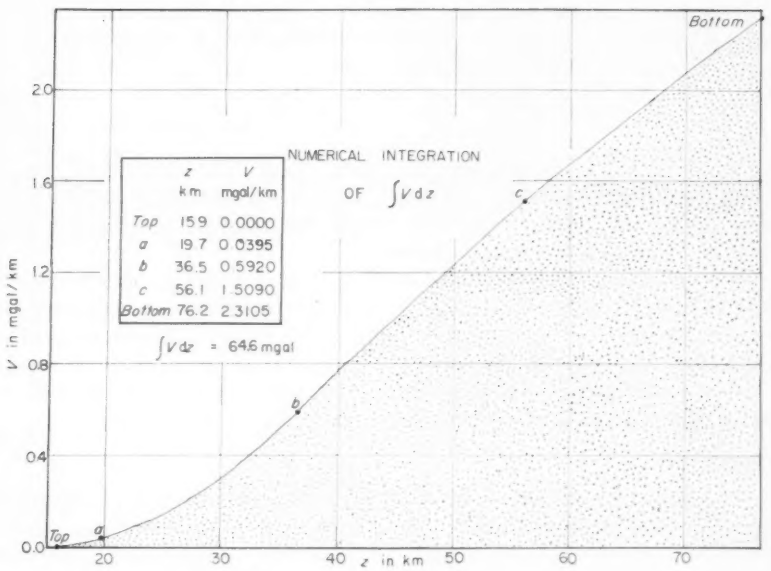

FIG. 3. Numerical integration of the integral $\int V dz$.

The first step is to pick out points on each contour in such a way that when they are joined in order, the irregular polygon so formed fits the contour closely. These points are marked by dots on the contours (Figure 2). The coordinates of these points are next determined. The z-coordinate of each point merely equals the depth of the contour below P. The x- and y-coordinates are determined by placing a transparent graph paper on the drawing of the contours. To determine the function V (that is, the gravity anomaly caused by the associated polygonal lamina of unit thickness) for each contour, all the data required are the coordinates of these points, the density of the body and the coordinates of the point P, at which the anomaly is being determined. These are punched on cards and fed into the IBM 650 . The function V is computed for each contour. These values are tabulated in Figure 3.

The numerical quadrature $\int V dz$ is also done entirely on the IBM 650. Figure 3 illustrates graphically the procedure involved in the integration. The value of V is plotted, for each contour, as a function of z. Parabolas are fitted to these points taken three at a time. These parabolas together form a continuous curve. The area between the z-axis and the continuous curve through the points, *Top*, *a*, *b*, *c*, and *Bottom*, is shown stippled in Figure 3. This area represents an approximation for the integral $\int V dz$, and is evaluated analytically by means of equation (9) by the IBM 650. This gives the value of the vertical component of the gravitational attraction of the massive body at the external point P.

The time spent in getting the data ready for the IBM 650 was about half an hour for this problem. The time taken by the machine to compute the anomaly was about 4 minutes. The total time spent is thus comparable with that taken by conventional methods. However, the evaluation of the anomaly at any other point in the neighborhood of the body M is achieved in only 4 minutes again. Thus, if the anomaly is evaluated at a number of points, the saving in time can be considerable.

Accuracy

Since the digital computer can be programmed to give any normally desired degree of precision, the accuracy of this method depends on how closely the irregular polygons fit the individual contours and on how precise the numerical integration is. These are considered in turn.

The polygons can, of course, be made to fit the contours as closely as desired merely by increasing the number of their sides. However, this increases the computing time. It will be recognized that the close fit of the contours is only important when a portion of the contour boundary lies close to the point at which the computation is being made. Then by fitting only such portions of the contour very closely, the accuracy of the integration can be maintained without increasing the computing time unduly. It can also be seen that even for points extremely close to the contour line, the evaluation of the integral being analytical, is exact, and one does not have to enlarge the scale as in graphical methods.

A quantitative assessment of the small error introduced by not fitting the contour lines exactly is difficult to make. The following example in which the gravity anomaly of a circular lamina is determined by this method should serve as a guide.

The anomaly per unit thickness , V, caused by a circular lamina can be determined analytically in a closed form at points along its axis and at points above its edge. A circular lamina of radius 100 km and density 0.5 gm/cc was chosen and it was approximated by an inscribed 72-sided regular polygon. The results of the anomaly computations for the polygon made on an IBM 650 are compared with the results obtained for the circular lamina in Table 1. The heights z of the points at which the computations are made are listed in the first column of Table 1. (These heights are chosen in order to obtain a whole number argument for the complete elliptic integral involved in the analytical expression for the gravity anomaly caused by a circular lamina at points vertically above its edge.) The computed values of V for the circular lamina are listed in column 2 for points along the axis and in column 4 for points along the vertical line through the edge. The corresponding values for the polygon as computed on the IBM 650 are listed in columns 3 and 5. It should be noticed that the differences for the two computations are very small except when the point at which the computation is being made lies close to the boundary of the lamina. Even in the worst case taken here the difference is less than one third of one percent of the total value.

The accuracy of the numerical quadrature is even more difficult to assess

TABLE 1

COMPARISON OF GRAVITATIONAL ATTRACTIONS OF CIRCULAR LAMINA AND INSCRIBED 72-SIDED REGULAR POLYGONAL LAMINA AT POINTS ON THE AXIS AND VERTICALLY ABOVE THE EDGE

Height Above Plane of Lamina (km)	Computed Value of Function V in Units of mgal/km			
	Points on Axis		Points above Edge	
	Circle (radius = 100 km)	Inscribed 72-sided polygon	Circle (radius = 100 km)	Inscribed 72-sided polygon
17.498	17.343	17.341	8.250	8.225
35.265	13.985	13.981	6.825	6.813
53.590	11.057	11.052	5.699	5.690
72.794	8.624	8.617	4.764	4.758
93.262	6.663	6.658	3.969	3.964
115.470	5.114	5.110	3.285	3.281
140.042	3.901	3.898	2.693	2.690
167.820	2.953	2.951	2.179	2.176
200.000	2.212	2.210	1.733	1.731

except in cases where the positions of the contour outlines can be obtained at all depths. This, of course, can be done only for bodies of regular geometrical shape or for very well surveyed bodies. In such cases, other methods of numerical quadrature, such as Gauss' method, can be used to enhance the precision.

In general the accuracy is mainly governed by the contour interval. Now, in making the numerical quadrature we have assumed that function V varies smoothly between contours. This is certainly as valid as an assumption that the depth of the surface of the body varies smoothly between contours. Thus, but for a single exception mentioned below, the accuracy of the method is not increased by interpolating new contours between known ones. This is not a limitation of the method; on the other hand it eliminates the labor of interpolating depths between contours while achieving the same degree of accuracy. The only exception is illustrated by an example. Suppose we are trying to determine the attraction of a long, vertical cylinder at a point at the same level as the top of the cylinder. Let us choose only three contours to define the cylinder, one at the top, one at the bottom and the third very near the bottom. The function V corresponding to the first contour will be zero, that corresponding to the other two contours will also be small if the cylinder is very long. Obviously, an interpolation of the function V will give erroneous answers in this case. This arises, of course, from the fact that our contour interval is much too large and there is a periodicity in the function V. Our basic criterion for evaluating the quadrature, that the function V varies smoothly between contours, is not satisfied.

TERRAIN AND ISOSTATIC CORRECTIONS

Local Terrain Corrections

The assumption of a flat earth is generally made in computing terrain corrections for local gravimetric surveys. For such cases the method described above

can be readily adopted. The contours that define the irregularly shaped three-dimensional body are now the topographic contours. To make the terrain corrections, an area much larger than the area in which the stations are located is chosen. (Also, since the terrain correction is being evaluated rather than the total Bouguer anomaly, one has to take into consideration whether the contours enclose the station at which the correction is being evaluated.) If it is desired to make the terrain corrections over only a limited area surrounding the station, as for example up to Hammer zone M, this can be accomplished by suitably programming the digital computer. This programming is done in such a way that when the computer is performing the line integral for the polygon, the integration is restricted to an area that lies within a circle described with the station as the center and the prespecified distance as radius. In other words, if a portion of the contour along which the line integral is proceeding lies outside this circle then this portion of the contour is replaced by the periphery of the circle itself. This adds, of course, somewhat to the computing time.

For two-dimensional features it is simpler to use the method given by Talwani, et al. (1959) to determine the terrain correction. In this method the attraction of two-dimensional bodies can be computed simply with a program for the IBM 650.

Regional Terrain Corrections

The evaluation of terrain correction for regional or geodetic work generally involves corrections to be made up to the outer radius of Hayford Zone O (166.7 km). For such a large area a spherical earth must be considered. However, Hayford and Bowie (1912) have shown that sufficient accuracy can be maintained if the earth be assumed flat up to the outer radius of zone L (28.8 km) and if the sea level surfaces in zones M (28.8 km to 58.8 km), N (58.8 km to 99.0 km), and O (99.0 km to 166.7 km) are also considered flat parallel planes, but 500 ft, 1,600 ft, and 4,500 ft, respectively, vertically below the sea level surface of the innermost zone. Further, it is easy to see that instead of circular zones, if 12-sided regular polygons are used for the boundaries of the different Hayford zones, the inaccuracy involved being a third order term is negligible. Making these assumptions our method can be used with a slight modification to obtain terrain corrections on a spherical earth. This is illustrated best by an example. In Figure 4, P' is the projection of the station (at which the terrain correction is being evaluated) on the map and AB is a portion of a contour along which the line integral is being evaluated. The outer peripheries of zones L, M, N and O are also shown in Figure 4. Now if this were a flat earth the value of the line integral along AB would be directly proportional to the anomaly caused by the triangular lamina $P'AB$. If we replace the triangle $P'AB$ by the quadrilateral $P'A_1k_1B_1$ at the same level as the contour, the polygon $A_1A_2k_2B_2B_1k_1$ 500 ft below the level of the contour, the polygon $A_2A_3k_3B_3B_2k_2$ 1,600 ft below the level of the contour and the polygon $A_3ABB_3k_3$ 4500 ft below the level of the contour, the sphericity of the earth would be adequately represented. The computations for the quadrilateral and the polygons can be made with the help of equation (6). If a portion of the

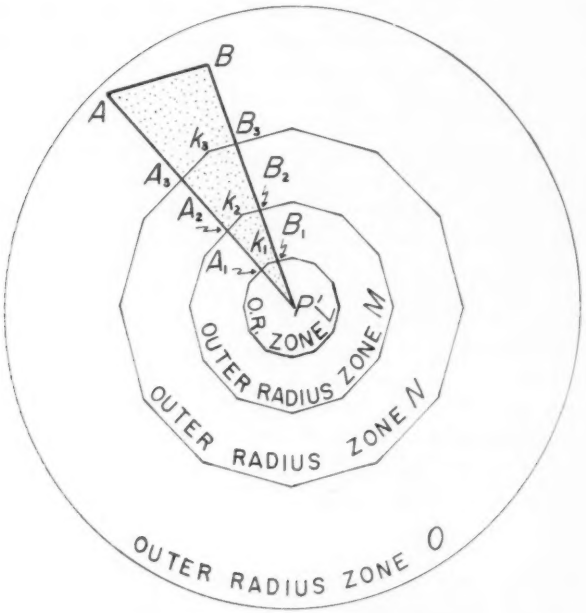

FIG. 4. Evaluation of the line integral along a contour segment on a spherical earth.

contour extends beyond the outermost zone, then, as in the case of the flat earth, this portion of the contour can be replaced by the periphery of the outermost zone.

It will be recognized that substantial advantages are realized over conventional methods. Firstly, the inaccuracy introduced by the division into compartments is eliminated. Secondly, the laborious process of estimating the height of each compartment is also eliminated. Thirdly, once the contours in a certain area are put in data form into the digital computer, the terrain corrections for all the stations in this area can be evaluated from the same data.

Isostatic Reductions

It is obvious that by replacing the height of the topographic contours by a corresponding depth to the Airy "isostatic surface" and replacing the density used for terrain corrections by the density contrast at the base of the crust, the isostatic compensation up to the outer radius of zone *O* can be readily obtained. As before, the sphericity of the earth can be taken into consideration and the contours restricted up to the outer radius of zone *O*. The present method is not able to obtain isostatic corrections beyond zone *O*. For this we have to consider existing methods and utilize the one which fits in most suitably with the evaluation of corrections up to zone *O* by the above method.

The cartographic method suggested by Heiskanen in which the isostatic compensations for certain outer zones are plotted on maps as contours, has the advantage of great simplicity and ready use. According to Heiskanen and Vening Meinesz (1958, p. 178) maps are available incorporating the contoured effects of topography and compensation in zones 18 to 1 for the whole of Europe and its neighboring areas and the U.S.A. Then, by combining the values from these maps with those obtained for the inner zones by the rapid method outlined above, isostatic reductions can be made quickly.

Heiskanen (1953) and Kukkamäki (1955) have suggested a "mass-line" method for the evaluation of both the topographic and isostatic reductions up to the antipodes. Their method envisages the division of the entire earth into spherical trapezoids 5′ by 5′, 10′ by 10′, 0°.5 by 0°.5, 1° by 1°, 2° by 2° and so on. The mean elevation of each trapezoid is estimated and stored as data in a high speed computer. Assuming these trapezoids to be "mass-lines" both the isostatic compensation and the terrain correction can be obtained at any station. However, this method requires the division of the earth into an enormous number of compartments and the estimation of the mean height for each compartment would be an extremely laborious task. For a system in which the computation beyond a distance of about 2° from the station would be performed by Heiskanen and Kukkamäki's method and within this distance by our method, the saving in time should be considerable, since a large majority of their proposed compartments lie close to the station and both the height estimation and the evaluation of the gravitational attraction for these will be eliminated. By using rectangular zones in both methods, the boundaries on either side of which the two methods operate, would be simply defined.

An alternative method for including the effect of curvature—possibly superior to that used above—would be the direct evaluation of the gravitational attraction of an irregular "polygon" on a spherical surface.

METHOD FOR HAND COMPUTATION

We have seen earlier that the integration over the z-axis can be easily done graphically instead of by using numerical quadrature methods. If a simple method were also available for evaluating the line integral around the polygonal boundary, it would be possible to compute the total anomaly for three-dimensional bodies without resorting to the use of high speed digital computers. But, as mentioned earlier, the exact expression for V (the gravity anomaly for a lamina of unit thickness) becomes tedious to "hand compute" when the number of sides of the polygon becomes larger than five or six. However, a good approximation for the value of V even when the number of sides is large, can be obtained by replacing the polygon by another one which fits it closely but whose sides are alternately parallel to the x- and the y-axes. For such a polygon (Figure 5), the value of the function V is given by the expression

$$V = k\rho[T - \sum (QRU)], \tag{10}$$

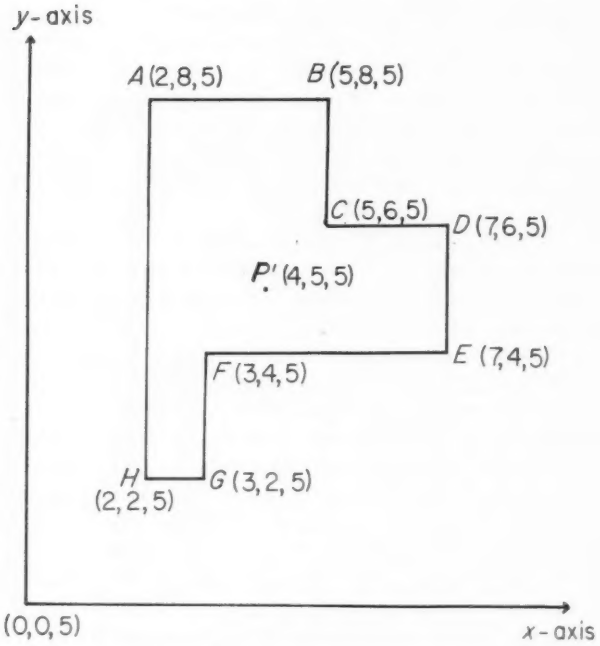

FIG. 5. Polygon used for "hand computation,"

where k and ρ represent as before the gravitational constant and the volume density, respectively. $T=2\pi$ when the projection of the point at which the anomaly is being evaluated, on the plane of the polygon lies within the polygon; $T=0$ when the projection lies outside the polygon. In the particular case when it lies on the boundary of the polygon, its value equals the angle subtended at this point by the adjacent sides of the polygon boundary. The summation is carried out over all the vertices of the polygon, the values of Q, R, and U being evaluated at each vertex from the following relations:

$$U = \left[\arcsin \frac{z}{(x^2 + z^2)^{1/2}} \frac{y}{(x^2 + y^2)^{1/2}} + \arcsin \frac{z}{(y^2 + z^2)^{1/2}} \frac{x}{(x^2 + y^2)^{1/2}} \right], \quad (11)$$

where

$R=+1$ if the product xyz is positive, or if $xyz=0$,
$R=-1$ if the product xyz is negative,

x, y, and z being the coordinates of the vertex of the polygon referred to the point at which the anomaly is being determined, as origin, and $Q=+1$ and -1

for successive vertices of the polygon. (For vertices B, D, $F \cdots$ in Figure 5 which are such that the next vertex in clockwise order has the same value of the x coordinate as at these vertices, $Q=+1$. For vertices A, C, $E \cdots$ where the same holds true for the y coordinate $Q=-1$.)

The value of U can be obtained from the accompanying chart (Figure 6), in which a family of curves (each curve for a different value of U) is plotted as a function of the ratios $x:y$ and $x:z$. It can be readily seen that the value of U can be obtained by interpolation from this chart for any set of values for x, y and z. However, we notice that when the value of $|x|$ is even moderately larger than both $|y|$ and $|z|$, the chart is difficult to use directly. The family of curves for various values of U begins to converge and it is difficult to determine the correct value of U at a given point. A simple device can be used to get over this difficulty. Since our choice of the x- and y-axes is purely arbitrary, we can interchange them. Then by interchanging the x and y coordinates for a point, the value of U remains unchanged. For example, let us determine U at a point with the x, y and z coordinates 50 km, 5 km, and 2.5 km, respectively. $|z/x|=0.05$ and $|y/x|=0.1$.

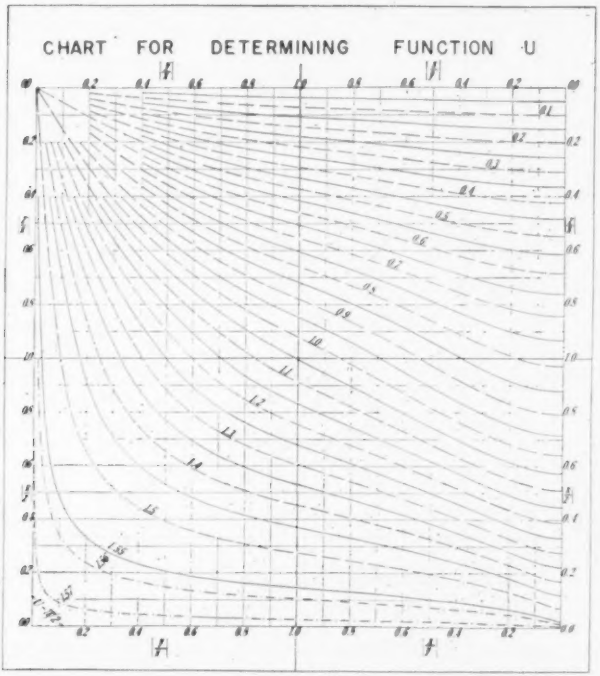

FIG. 6. Chart for determining function U. (Figures 6a, 6b, 6c, and 6d reproduce the four portions of Figure 6 in a size suitable for use.)

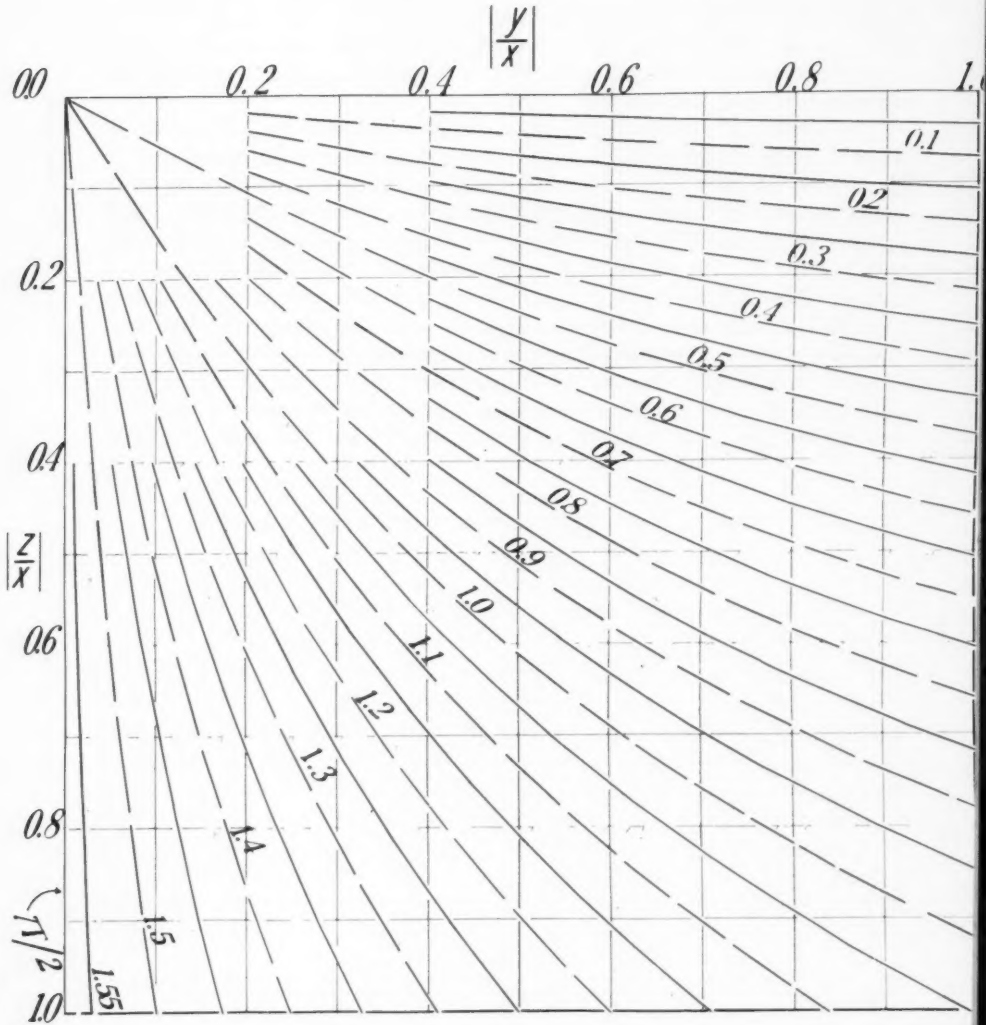

FIG. 6a. Upper left quarter of Fig. 6.

From the chart (Figure 6) we can approximately determine U to be equal to 0.45, but the precision for this determination is small. Now interchange the x and y coordinates. The new coordinates are $x=5$ km, $y=50$ km, $z=2.5$ km. This gives $|z/x|=0.5$ and $|x/y|=0.1$. From the chart a value of 0.466 for U is determined.

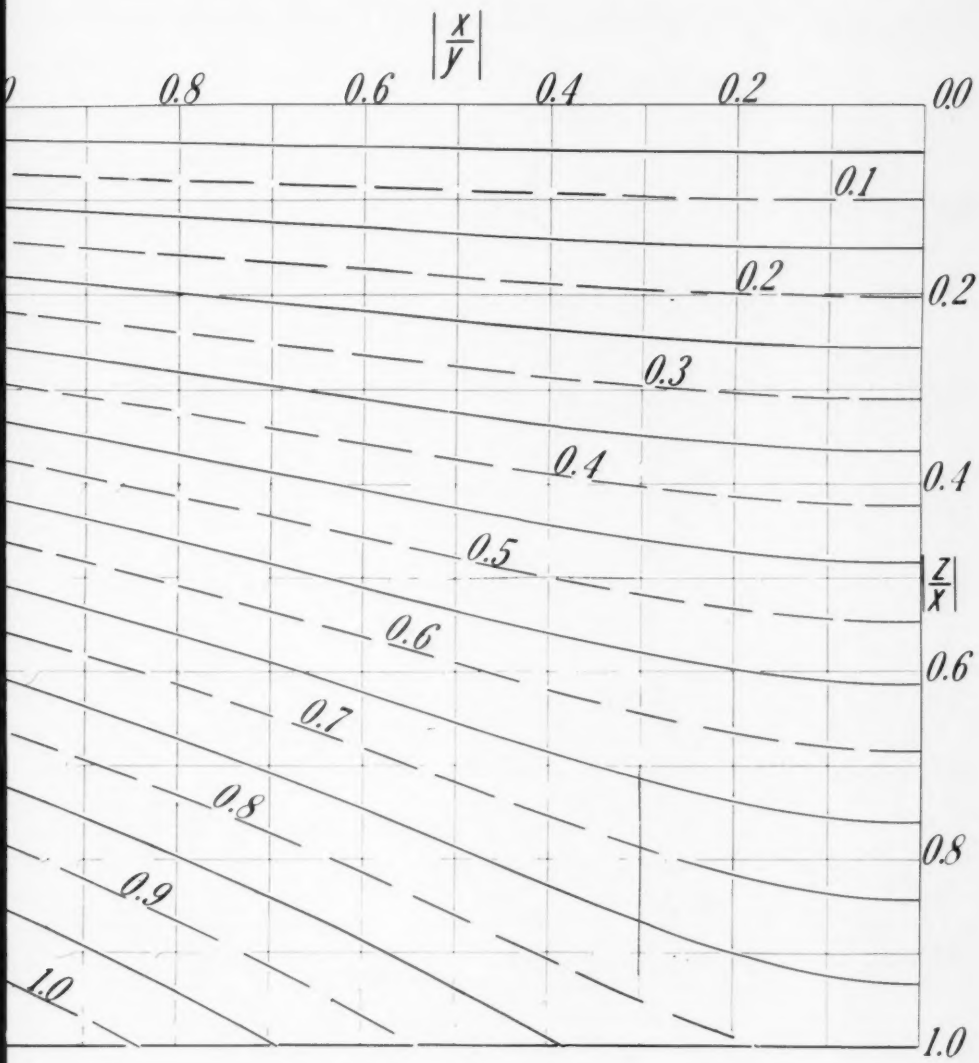

FIG. 6b. Upper right quarter of Fig. 6.

The correct value is 0.4661. We see that we are able to increase our precision considerably in determining U. When $|x| = \infty$, with a finite value of y, U can not be determined without making this interchange of coordinates. However, even

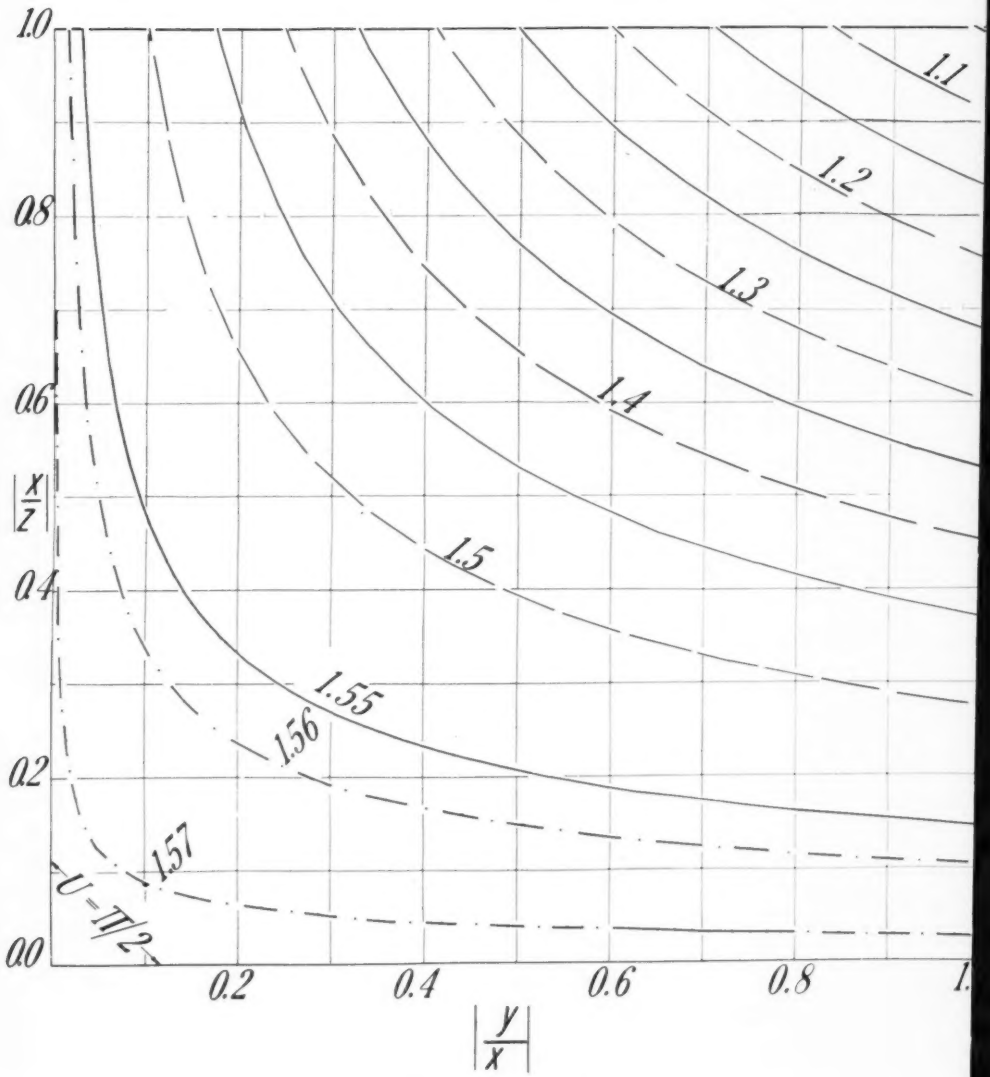

FIG. 6c. Lower left quarter of Fig. 6.

when $|x|$ is not very large, the interchange of coordinates can be used as a ready check to see if the correct value of U has been determined. The physical meaning of U is interesting. $(\pi/2-U)$ represents the solid angle subtended at a point by

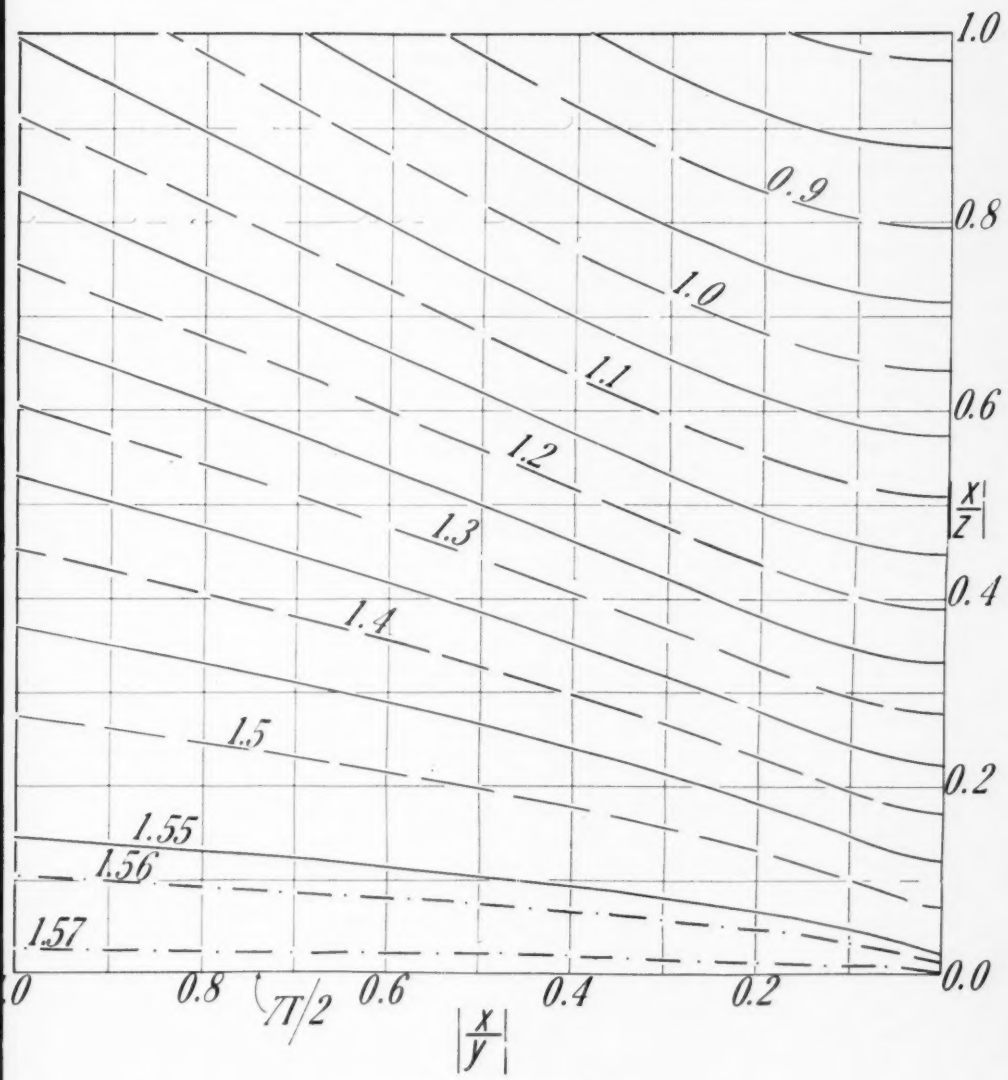

FIG. 6d. Lower right quarter of Fig. 6.

a horizontal rectangle at a distance z below it, the sides of the rectangle having lengths x and y, and one of the corners of the rectangle lying directly below the point.

The value of U having been obtained from the chart, the value of V can be determined by means of equation (10). V is then plotted as a function of z, the depth of the polygonal lamina. This is repeated for laminae representing other contours. A smooth curve is then drawn through the (V, z) plots and the area bounded by this curve, the z-axis, and the two lines parallel to the V-axis (corresponding to the values of z which give the top and the bottom of the irregularly shaped body) is determined. This area gives the total anomaly caused by the body. If z is expressed in km, ρ in gm/cc and a value of 6.67 is chosen for k, the result is obtained directly in milligals.

The following example in which the various steps in the "hand computation" of the function V for the polygon in Figure 5 are given, should be useful.

Let the coordinates of the vertices of this polygon be as indicated in Figure 5. These are listed in column 2 of Table 2. We have tacitly assumed in our discussion previously that the point at which the computations are being made is located at the origin. This is, of course, not true in general. Let the coordinates of this point, P, instead, be (4, 5, 0). (Since the function U is dimensionless the units in which the various coordinates are listed are immaterial.) In Figure 5, P' is the projection of P on the plane of the polygon. In column 3 the coordinates of the vertices of the polygon with respect to P are listed. In column 4 the ratios $|x/y|$ or $|y/x|$ and $|x/z|$ or $|z/x|$ are evaluated. The curves in Figure 6 have been constructed only for coordinate ratios less than unity, for the evaluation of the function U. Thus, when $|x| < |y|$ the ratio $|x/y|$ is used, when $|x| > |y|$ the ratio $|y/x|$ is used. Similarly, when $|x| < |z|$ the ratio $|x/z|$ is used while for $|x| > |z|$ the ratio $|z/x|$ is used. (For instance, for vertex A, $|x/y|$ is computed; but for vertex D, $|y/x|$ is computed.) Next a point is located on the chart in Figure 6 whose coordinates are given by the ratios just determined. For A, $|x/y| = 0.667$ and $|x/z| = 0.4$, and this point is located in the bottom right quadrant of the chart. This point lies between the curves for U having the values 1.35 and 1.40. By interpolation a value of 1.380 is obtained. This gives the value of U at A (column 5). As a check for this value, x and y, the coordinates of A are interchanged. For the interchanged coordinates $x = +3$, $y = -2$, and $|y/x| = 0.667$ and $|x/z| = 0.6$. These ratios are noted in column 6. Again, a point with these coordinates is located, this time in the bottom left quadrant of the chart in Figure 6. By interpolation a value of 1.378 is obtained for U at this point. This is noted in column 7. Actually, the two values obtained for U should be identical. The difference represents the errors made in the interpolations. For evaluating V, a mean value of 1.379 is adopted for U (column 8). The product xyz at A is -30. This is negative, thus the value of $R = -1$ (column 9). The value of the y coordinate at A equals the value of the y coordinate at B. Thus $Q = -1$ (column 10). The product $QRU = +1.379$ (column 11). Similarly, the product QRU is evaluated at all the other vertices of the polygon and $\sum(QRU)$ is evaluated by adding all the terms. The sum is $+5.698$. The value of T is 2π since the polygon subtends this total angle at P'. Then from (10)

$$V = k\rho[2\pi - 5.698]. \tag{12}$$

TABLE 2

VARIOUS STEPS INVOLVED IN THE "HAND-COMPUTATION" OF FUNCTION V

(1) Vertex	(2) Coordinates of Vertex			(3) Coordinates of Vertex referred to point of computation			(4) Coordinate Ratios				(5) U	(6) Interchanged Coordinate Ratios				(7) U After Interchange	(8) Mean Value of U	(9) R	(10) Q	(11) QRU
				x	y	z	$\lvert x/y\rvert$	$\lvert y/x\rvert$	$\lvert x/z\rvert$	$\lvert z/x\rvert$		$\lvert x/y\rvert$	$\lvert y/x\rvert$	$\lvert x/z\rvert$	$\lvert z/x\rvert$					
A	2	8	5	−2	3	5	0.667		0.400		1.380		0.667	0.600		1.378	1.379	−1	−1	+1.379
B	5	8	5	1	3	5	0.333		0.200		1.471		0.333	0.600		1.469	1.470	+1	+1	+1.470
C	5	6	5	1	1	5	1.000		0.200		1.530	1.000		0.200		1.530	1.530	+1	−1	−1.530
D	7	6	5	3	1	5		0.333	0.600		1.469	0.333		0.200		1.471	1.470	+1	+1	+1.470
E	7	4	5	3	−1	5		0.333	0.600		1.469	0.333		0.200		1.471	1.470	−1	−1	+1.470
F	3	4	5	−1	−1	5	1.000		0.200		1.530	1.000		0.200		1.530	1.530	+1	+1	+1.530
G	3	2	5	−1	−3	5	0.333		0.200		1.471		0.333	0.600		1.469	1.470	+1	−1	−1.470
H	2	2	5	−2	−3	5	0.667		0.400		1.380		0.667	0.600		1.378	1.379	+1	+1	+1.379

$\Sigma(QRU) = +5.698$

If a density of 1 gm/cc is assumed for the polygonal lamina, a value of 6.67 for k gives the value for V in mgal/km. On evaluating (12), a value of 3.90 mgal/km is obtained for V. This compares with an actual value of 3.91 mgal/km. Thus the errors due to interpolations while determining U from the chart are very small.

CALCULATION OF MAGNETIC INTENSITY

For a magnetized body vertically polarized, the vertical component of magnetic intensity may be calculated in a manner analogous to that used above for obtaining the gravity anomaly. For a vertically polarized horizontal polygonal lamina, the vertical component of magnetic intensity, calculated at an external point, is proportional to $\partial V/\partial z$, where V is obtained as before from (6). The expression for $\partial V/\partial z$ can be obtained in terms of the coordinates of the corners of the polygon and programmed for solution by a high speed digital computer. The vertical component of the magnetic intensity caused by the entire body is proportional to

$$\int_{z_{\text{bottom}}}^{z_{\text{top}}} \frac{\partial V}{\partial z}\, dz.$$

This integral is evaluated numerically as in the gravitational case, and the magnetic intensity calculated to a high degree of precision. An alternative method is suggested by the integral above. It reduces to $V_{\text{top}}-V_{\text{bottom}}$ when the sides of the body are vertical. Then by approximating the body by a number of bodies with vertical sides, the magnetic intensity can be calculated from the values of V obtained at different heights. The chart for hand computation can be used in this case.

For bodies that are not vertically polarized, the component of magnetic intensity in the direction of polarization can be obtained similarly by defining the body by contours in a plane perpendicular to this direction. This orthographic projection of the topographic map of the body was originally suggested by Henderson and Zietz (1957).

For bodies which are magnetized by induction alone in the earth's field the direction of the polarization is of course the same as the direction of the earth's field. The orthographic projection is then made perpendicular to this direction and the intensity component evaluated along this direction. The evaluation of this component is very useful because it closely approximates the total intensity anomaly caused by the body in the presence of the much larger intensity of the earth's field. For bodies that have a predominant remanent polarization, the orthographic projection has to be made at right angles to the direction of total polarization—the vector sum of remanent and induced polarizations, which may in general be different from the direction of the earth's field. The component of the anomaly is, by the method mentioned above, determined along the direction of total polarization.

ACKNOWLEDGMENTS

The authors wish to thank their co-workers at Lamont Geological Observatory for many profitable discussions during the preparation of this paper.[1] The Watson Scientific Computing Laboratory allowed us the use of the IBM 650 on which the computations for this paper were made. For that, as well as for the use of other equipment, the authors wish to express their grateful appreciation. E. S. Skinner and A. E. Trefzer assisted in the computations and the drafting of illustrations. This research was carried out under contracts from the Office of Naval Research and the Bureau of Ships of the U. S. Navy.

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[1] J. Hirshman was especially helpful in the preparation of the part dealing with the calculation of magnetic intensity.

GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 226–249, 7 FIGS.

THE ELECTROCHEMICAL MECHANISM OF SULFIDE SELF-POTENTIALS*

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ABSTRACT

Self-potentials associated with a sulfide ore body result from the ohmic potential drop within the country rocks. The electric current is produced by separate but simultaneous reduction of oxidizing agents near the surface and oxidation of reducing agents at depth. The ore does not participate directly in either reaction, but serves as a conductor to transfer the electrons from the reducing agents to the oxidizing agents. The possibility for the above reactions to occur depends upon differences in oxidation potential of ground waters at different depths. In the zone of weathering, the oxidation potential is controlled by the reduction mechanism of oxygen, and ranges in value from 0.2 to 0.7 volt (on the hydrogen scale). If the ore tends to oxidize at some lower potential, then the latter is the available one. In the zone beneath the water table, the potential is probably controlled by the oxidation-reduction equilibria of iron-rich minerals, and ranges in value from 0 to −0.3 volt. The available potential is independent of ore type. The maximum potential difference available to produce natural currents is estimated at: graphite 0.8, pyrite 0.7, covellite 0.6, chalcocite 0.5, galena 0.3 volt. Self-potentials will be large if the ore body (1) is composed of minerals difficult to oxidize, (2) has low electrical resistance (physical continuity together with low resistivity), (3) extends vertically across the water table, and (4) exists close to the surface.

SELF-POTENTIAL BACKGROUND

Any hypothesis regarding the electrochemical mechanism of self-potentials must be consistent with the field observations. Field measurements extend back more than 100 years, to the work of Fox (1830), but systematic use of the method dates from about 1920. An immense amount of field work has been carried out since that time. Based upon a review of approximately 150 papers dealing with self-potentials near ore bodies, together with generally accepted data relating to the geology of ore deposits, the following generalizations are proposed. (Self-potentials as observed in oil exploration represent a different phenomenon, reasonably explained in terms of salinity gradients and the special properties of clays and shales).

1) The minerals which produce strong self-potential anomalies most consistently are pyrite and pyrrhotite.

Most of the strong anomalies are associated with massive ore bodies or continuous veins, although it does not follow that all structures of this type will produce strong anomalies. The evidence regarding disseminated ore bodies is less clear.

2) Other minerals which are capable of producing strong anomalies include chalcopyrite, chalcocite, covellite, graphite, and anthracite.

* Manuscript received by the Editor October 9, 1959.

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3) Self-potential anomalies have occasionally been reported in connection with other copper sulfides, cobalt ores, manganese oxides, siderite (Wilckens, 1955), alunite (Kruger and Lacy, 1949), magnetite, pegmatites (Heiland, 1940).

4) All of the minerals in (1) and (2) share the characteristic that they conduct electricity by the flow of electrons (rather than ions) and are relatively good conductors. (Normal rock conductivity is electrolytic.)

5) The order of magnitude of a large self-potential anomaly is 0.5 volt. Higher published values include 1.0 volt (Shibato, 1949, graphite), 1.3 volt (Fujita, 1926) and 0.7 volt (Kruger and Lacy, 1949, alunite). The voltage reference level is presumably a point at infinity.

6) Self-potential anomalies appear to be predominantly negative in the vicinity of the upper portion of the ore body.

Positive anomalies have been reported occasionally, particularly with graphite. Wilckens (1955) cites six graphite deposits on three continents, two of which showed positive anomalies. Kelly (1945) proposes an explanation for one of these which, if correct, would imply that a negative anomaly is normally expected. Okabe et al. (1957) observed +200 mv over a sulfide vein, with comparable negative anomalies on walls of graphite schist.

A few attempts have been made to measure the depth distribution of potentials. Militzer (1953, as cited by Wilckens) observed an increase of negative potential at depth, reaching −300 mv at 600 meters. Ohashi et al. (1958) found that equipotentials were roughly concentric about the apex of the ore body, although the measurements were confined to very shallow depths. Fuchida (1952) studied the three-dimensional distribution by measurements in mines and in drill holes, with inconclusive results.

The polarity of the supposed "electrodes" within the ore body has been a source of confusion, perhaps because of the awkward convention which assigns opposite directions to a flow of electrons and a flow of current. Wilckens (1955) describes the problem. We propose to avoid it by considering only the actual flow of ions or electrons.

7) At least part of the ore body must lie in a zone of active oxidation.

As illustration, Brant (1948) mentions that sulfides and arsenides at MacLeod Cockshutt gold mines gave −200 mv anomaly under shallow sand, yet gave no anomaly 100 ft away under shallow muskeg. He points out that only shallow ore bodies have ever been located by self-potentials, which suggests that the currents may originate in the shallow portion. Poldini (1938) describes an ore body in the Vardor District of Jugoslavia which produced self-potentials under oxidizing condition, but failed to do so underneath a nearby peat layer.

8) The self-potential phenomenon is relatively stable in time.

Takahashi (1952) found that the effect of climatic variations was small.

Poldini (1938) reported no perceptible variation of self-potentials over an ore body for a period of 10 years, including measurements during different seasons. Bukhnikashvili and Kebuladze (1955), found variations up to 29 percent during two summer months. Annual variations of at most several mv were observed by Ohashi (1955) with anomalies of a few hundred mv.

9) Self-potentials associated with graphite and galena present a special problem for any proposed theory.

Graphite is the only non-sulfide which produces more than occasional self-potential anomalies comparable in magnitude with those of sulfides, and it does not (despite a contrary statement by Poldini, 1938) normally undergo significant oxidation. On the other hand, galena rarely produces measureable anomalies although it is a sulfide, an excellent electrical conductor, and oxidizes more easily than most sulfides.

10) The region above the water table near sulfide ore bodies is usually characterized by high acidity (pH = 2–5) and an abundance of free oxygen. Below the water table, free oxygen is virtually absent and the water is usually slightly basic (pH = 7–9).

PREVIOUS THEORIES

Group 1: Theories in which self-potentials are directly produced by the oxidation of sulfides

Nearly all theories of the origin of self-potentials emphasize the importance of sulfide oxidation; in addition, most theories require that the sulfide body extend continuously from a zone of oxidation into a zone relatively free from oxidation. Less agreement exists on the role of the oxidation process, however. Some theories equate the self-potential mechanism to the oxidation process, others consider the mechanism to depend secondarily upon oxidation (for example, through the products of oxidation), while still others treat oxidation as irrelevant. Nowhere in the literature have we found a precise statement regarding the electrochemical half-cells and the involved ions which support the observed currents.

The case for the first group of theories is stated by Jakosky (1950, p. 444): "Surface water, carrying absorbed oxygen, creates a natural large-scale galvanic cell as a result of the oxidizing process." Poldini (1938) mentions this possibility among others, and a similar opinion appears to be held by Eve and Keys (1954) and Brant (1955). No specific electrochemical mechanism is proposed, however.

Group 2: Theories in which sulfide oxidation establishes necessary prior conditions for the self-potential mechanism

Most self-potential theories fall within this classification. Heiland (1940, p. 668) describes the process more explicitly than most. After specifying a two-

step oxidation reaction for pyrite, which yields limonite and sulfuric acid, he states that a potential difference is set up because the oxidized minerals have a lower solution pressure than the unaltered minerals beneath the zone of oxidation. From his sketch (Figure 10–21), he appears to visualize a cell which forms gaseous hydrogen at the cathode and oxygen at the anode. Dobrin (1952) presents the same argument. C. and M. Schlumberger (1922) describe a similar cell (see Group 3) in which the hydrogen combines with hydroxyl ion to form water in the oxidation zone, while oxygen goes into solution at depth (or oxidizes the ore if it is oxidizable). In their view, the oxidation process serves as a depolarizer to facilitate removal of the hydrogen, a situation known to occur in corrosion.

A related theory proposes that the electric currents are produced by the difference in acidity of the ground waters above and below the water table. If sulfuric acid is an end product of sulfide oxidation, then it should produce lower pH near the upper end of the ore body. Kelly (1945) reports field measurements which confirm the expected pH difference, and laboratory measurements to demonstrate that such a difference will produce electric currents. The same mechanism has been proposed by Matsubara (1930) and Nakabayashi (1949).

Wilckens (1955) proposes an oxide-sulfide cell. Sulfide oxidation yields sulfuric acid, which dissolves the soluble portion of the ore and produces ferrosulfate. This is oxidized by oxygen to brown iron ($Fe_2O_3 \cdot H_2O$). The oxide forms an "oxide electrode" which supplies metal ions to the surrounding solution. The ions determine the potential; their concentration depends upon solubility of the oxide, hence upon pH. He considers that the concentration cell produced by pH-differences also contributes to self-potentials, to some extent independently of the oxide-sulfide cell. The exact reactions are not specified. Rao (1945) proposes that oxidation of ferrous carbonate into limonite enters into the self-potential mechanism.

Group 3: Theories in which sulfide oxidation is irrelevant

C. and M. Schlumberger (1922) and Poldini (1938) propose what is essentially an oxygen concentration cell. This was referred to above. They point out that the concentration of dissolved oxygen is considerably greater above than below the water table. Near the surface, oxygen combines with hydrogen ion to form hydroxyl ion or water; at depth, the reverse takes place. By the Nernst equation, this yields a potential which is proportional to the logarithm of the oxygen concentration ratio. Poldini recognized a difficulty which he labelled the "gossan problem," namely that the postulated cell reaction should prevent sulfide oxidation (gossan formation) at the surface. He concludes that high cell resistance together with minor heterogeneities can resolve the apparent contradiction.

The remaining theories relate to electrical potentials which undoubtedly exist, but which seem unlikely to contribute significantly to sulfide self-potentials. While they may modify the potential field and increase the difficulty of inter-

pretation, we believe they can be eliminated from consideration as a primary mechanism. They include electrical double layers at the sulfide surface (Shibato et al, 1954; Ohashi, 1956), diffusion potentials (Nakabayashi, 1949), electro-osmotic potentials (Bilinsky, 1938), telluric current potentials due either to ohmic drop or to induced polarization (Brant, 1955; Wilckens, 1955), the effect of atmospheric potential gradients on inhomogeneous conductors (Brant, 1955), and certain phenomena related to the flow of electrolytic solutions through porous media, known variously as electro-filtration, streaming, flow, and zeta potentials (Poldini, 1938; Rao, 1945; Nakabayashi, 1949; Meisser, 1952; Militzer, 1953).

ELECTROCHEMICAL BACKGROUND

The presentation below essentially follows Pourbaix (1949) and Latimer (1952, 1957). Pourbaix reduces electrochemical reactions in aqueous media to the general form:

$$aA + w\mathrm{H_2O} = bB + mH^+ + ne^-, \tag{1}$$

where e^- indicates electron, and the other lower case letters specify mole numbers of participating substances. The conditions for thermodynamic equilibrium are then expressible in terms of the two independent variables: pH, defined as $-\log(\mathrm{H^+})$, which determines the influence of the hydrogen ions, and E, the oxidation potential, which determines the influence of electrons. Any specific reaction may be independent of pH or the oxidation potential, in which case m or n is respectively zero.

Latimer (1952) defines an oxidation-reduction reaction as a chemical reaction which involves the exchange of electrons. If a substance loses one or more electrons in a reaction, it is said to be oxidized and is called a reducing agent: reduction is a chemical process of acquiring one or more electrons by an oxidizing agent. Any oxidation-reduction reaction may be split into two "half-cell reactions" or "couples," that indicate the mechanism by which the electrons are transferred from the reducing agent to the oxidizing agent. Equation (1) represents such a half-cell reaction, when $n \neq 0$. To resolve a disagreement regarding the convention of the electrode sign, Latimer (1957) proposes to express the relationship of the oxidation potential of a half-cell reaction to the free energy change of the reaction, ΔF, as

$$\Delta F = nfE, \tag{2}$$

where $f = 23{,}070$ cal/mole (Faraday's constant).

Since any oxidation-reduction reaction involves only the difference in potential between two half-cell reactions, an absolute potential is not required. The following reaction is usually chosen as a reference couple:

$$\mathrm{H_2} = 2\mathrm{H^+} + 2e^-, \qquad \Delta F^0 = 0, \quad \text{and} \quad E^0 = 0. \tag{3}$$

The oxidation potential in this hydrogen scale is often called Eh. It is a potential

measured with reference to the standard hydrogen electrode based upon reaction (3).

Applying the second law of thermodynamics to the system under consideration, we arrive at an equation similar to the so-called Nernst equation. This specifies the conditions for thermodynamic equilibrium at 25° C and under one atmosphere of pressure:

$$\mathrm{Eh} = \mathrm{Eh}^0 - \frac{0.0591m}{n}\,\mathrm{pH} + \frac{0.0591}{n}\left[-a \log (A) + b \log (B)\right] \text{ volts.} \quad (4)$$

(A) and (B) designate activities (approximately, concentration) of the reactant and product, respectively. Eh° is the standard oxidation potential for the reaction, corresponding to the unit activities of all chemical species involved.

The above method reduces the significant variables to Eh, pH and the activities of ions of an element under consideration. The simplification becomes very useful when applied to a multi-component system where the exact composition is unknown, although all three are dependent upon the over-all equilibrium of the system and not vice versa. The application to the description of geochemical systems is discussed by ZoBell (1946), Mason (1949) Garrels (1954), and others.

For a particular reaction, Pourbaix chooses to present equation (4) in a graphical form, as an Eh-pH diagram. For example, the reaction:

$$\mathrm{Cu} = \mathrm{Cu}^{++} + 2e^-, \qquad \mathrm{Eh} = 0.337 + 0.0295 \log (\mathrm{Cu}^{++}), \quad (5)$$

may be plotted for various cupric ion activities as shown in Figure 1. We infer from the diagram that the potential of a copper electrode immersed in a 10^{-2} M. (activity) solution of cupric sulfate will approach an equilibrium value of 0.278 volt, and that increase in acidity will not change this potential. The Eh of the solution, as measured with an inert metallic electrode, will also approach this value.

The effect of hydrolysis on the equilibrium potential of a metal-metal ion system can also be shown in such a diagram. If pH is increased in the above solution by adding a base, hydrolysis of cupric ion will result:

$$\mathrm{Cu}^{++} + 2\mathrm{H_2O} = \mathrm{Cu(OH)_2} + 2\mathrm{H}^+, \qquad \log (\mathrm{Cu}^{++}) = 4.60 - 2\ \mathrm{pH}. \quad (6)$$

The activity of the cupric ion becomes a function of pH due to hydrolysis. Substitution of equation (6) in (5) yields:

$$\mathrm{Cu} + 2\mathrm{H_2O} = \mathrm{Cu(OH)_2} + 2\mathrm{H}^+ + 2e^-, \qquad \mathrm{Eh} = 0.610 - 0.0591\ \mathrm{pH}. \quad (7)$$

This equation supersedes equation (5) in basic solution, as indicated by the inclined solid line in Figure 1.

If a strong oxidizing agent is added to the above solution, the Eh of the solution will jump to a much higher value than the equilibrium value for the Cu-Cu^{++} system, whereas the potential of the copper electrode will remain near the latter value. Addition of a ferric salt, for example, will raise the Eh of the solution to

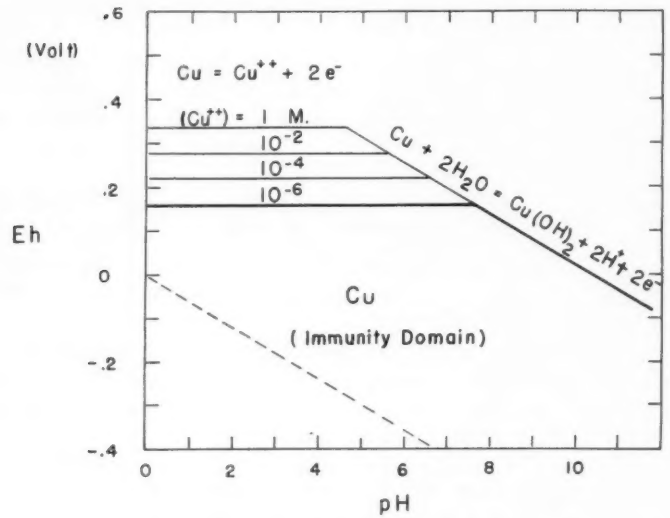

FIG. 1. Sample Eh-pH diagram, for the Cu-H_2O system at 25°C.

a value determined by the activity ratio of ferric ion to ferrous ion in the solution:

$$Fe^{++} = Fe^{+++} + e^-, \qquad Eh = 0.771 + 0.591 \log \frac{(Fe^{+++})}{(Fe^{++})} \cdot \tag{8}$$

In this condition, active oxidation of copper by ferric ion will take place spontaneously. The reaction will proceed until enough copper is oxidized to cupric ion and ferric ion reduced to ferrous ion, so that the potentials given by equations (5) and (7) become identical at some intermediate value between the two initial values.

In general, the spontaneous oxidation of an electrode by the surrounding solution is possible, if the Eh value of the solution is higher than the potential of the electrode. Similarly, reduction of the electrode by the solution is possible, if the Eh of the solution is lower than the electrode potential of the former.

Pourbaix introduces the concept of the *immunity domain* of a metal to be defined on an Eh-pH diagram; it is based on the assumption that a bare metal does not oxidize unless more than 10^{-6} M. activity of the metal can be dissolved into the surrounding solution. The limit of 10^{-6} M. is somewhat arbitrary, but practical. Within this domain, the single electrode potential of the metal equals the Eh of the solution, since the activity of the metal ion in the solution will quickly be adjusted with virtually no effect on the solution; if the solution is oxidized or reduced so that its Eh value rises or falls, the metal will undergo vir-

tually no chemical change, and will act as an inert metallic conductor. This situation generally arises for noble metals (e.g. platinum) under diverse Eh-pH conditions, for copper and lead under restricted reducing conditions, but never for most metals in aqueous solution. The region marked as such in Figure 1 indicates the immunity domain of copper.

An electrochemical cell with a liquid junction separating two solutions will function as an oxidation-reduction cell, if the Eh values of the solutions are not equal, and if each Eh value lies within the immunity domain of its respective electrode. The connection of the two electrodes by a conducting wire will permit a spontaneous electric current to flow from the electrode immersed in the solution of higher Eh to the electrode in the solution of lower Eh within the wire, and in the reverse direction within the solutions. The current will continue as long as the difference in Eh exists between the solutions. This point has an important bearing on the proposed self-potential mechanism to be described later.

PROPOSED MECHANISM

Limitations imposed by the Field Observations

The problem consists in specifying, with as much precision as possible, the electrochemical mechanism by which natural currents arise in the vicinity of ore bodies. The main outlines of the mechanism can be deduced from the observational data presented under Self-Potential Background.

(1) The mechanism must be capable of producing electric current over large volumes and for long periods of time. Potentials of the order of a few hundred mv, often encountered in field surveys in regions of flat topography, can only originate in an *IR* drop produced by currents flowing through the earth. This is required by the nature of the copper-sulfate field electrodes.[1] An alternative proposal, static double layers developed within the country rocks as suggested by Ohashi (1956), can be rejected from the analogy of the model to a leaky condenser.

(2) A substantial source of energy is involved. Energy will be dissipated when current flows through a resistive medium. The source must be stable over

[1] The question is sometimes raised as to whether the two field electrodes, spaced several hundred ft apart, might record a potential difference due to Eh or pH dissimilarities in the groundwater at the two locations. The overall cell is:

$$Cu/Cu^{++}(C)/\text{solution } (Eh_1, pH_1)/\text{solution } (Eh_2, pH_2)/Cu^{++}(C')/Cu.$$

Although potentials exist at the three liquid junctions, the external circuit measures the potential difference produced by the two reactions:

$$\text{at the left electrode: } Cu = Cu^{++}(C) + 2e^-$$
$$\text{at the right electrode: } Cu^{++}(C') + 2e^- = Cu.$$

The potentials will be equal and opposite, hence cancel, provided the Cu concentration is equal in both cases ($C = C'$) and no temperature or pressure differences exist. It follows that properly designed electrodes will not respond to local Eh or pH differences. As noted under PREVIOUS THEORIES, *Group 3*, however, minor variations up to a few tens of a mv may arise due to diffusion or other causes.

long periods of time, since the self-potentials are stable in time, and it must be active in the vicinity of sulfide ores under conditions favorable to oxidation. There seems little reason to doubt, as most authors have assumed, that this source of energy is chemical oxidation of the materials of the earth's crust by atmospheric oxygen.

(3) The mechanism must provide for the transfer of net electric charge across the ore-electrolyte boundaries. The kinds of ore which produce self-potentials conduct electricity by the flow of electrons, whereas the surrounding rocks conduct by the movement of ions in pore solutions. A closed electric circuit comprising conductors of both types necessarily involves the transfer of electrons across the boundaries of the two. A chemical process accompanying the transfer corresponds to one-half of a complete oxidation-reduction reaction; it is called a "half-cell" reaction or "couple."

(4) Two separate half-cell reactions of opposite nature, one anodic and the other cathodic, are required. An electrochemical cell differs from an ordinary oxidation-reduction reaction in that the two half-cell reactions must be separated in space and coupled through a medium of electronic conduction; the oxidant and the reductant do not come into direct contact with each other. The two half-cell reactions may be chemically unrelated, but must be balanced in the number of electrons; either one can limit the other in this respect.

(5) Any combination of two half-cell reactions must be such that available energy is evolved as the result of the cell reaction. This is required from the spontaneous nature of self-potentials. The electric current flows as the result of the cell reaction, and not vice versa. First, there must be a difference in oxidation potential between a pair of half-cell reactions. Second, the relative positions of the reactions are given, once the direction of the electric current is fixed, since a spontaneous electric current flows in a direction which tends to minimize the difference in the oxidation potentials.

(6) The half-cell reaction taking place near the surface must be cathodic (the substance involved is reduced), and the one at depth anodic (the substance is oxidized). This statement follows from the field data. Most surveys report a negative electrical center over the apex of the ore. The consequent directions of electron and ion flows are shown in Figure 2.

The preceding considerations permit us to eliminate some of the proposed theories. No theory is tenable which attributes self-potentials directly to the ore oxidation processes. Figure 2 shows that the electrons which are supplied to the upper end of the ore body in the oxidizing zone *must have travelled through the ore*, the oxidation of the ore near the surface, however, will not use these electrons but rather will furnish additional electrons. To illustrate, the initial step for the oxidation of covellite proceeds as

$$CuS = Cu^{++} + S + 2e^{-}.$$

Positive ions are released to the solution, and electrons are taken up by the

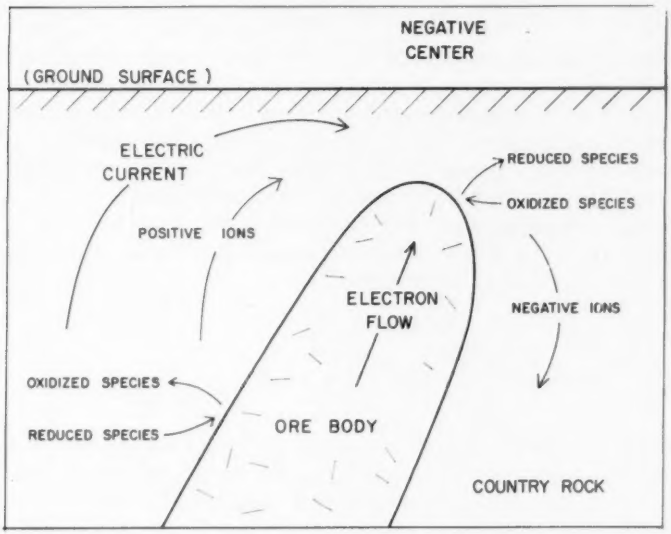

FIG. 2. Flow directions implied by a negative center over the apex of an ore body.

oxidizing agents acting on the ore. No net negative charge need be supplied from the remaining portion of the ore. Clearly, then, self-potentials are not caused directly by the near-surface oxidation of the ore. The reducing conditions prevailing at depths, however, inhibit this mechanism: the ore will not be oxidized before the surrounding reducing agents are mostly exhausted. This point will be discussed below.

Supporting evidence comes from graphite self-potentials. Graphite oxidizes at a negligible rate in an aqueous environment, so a mechanism which is directly dependent upon the oxidation of ore would be unable to account for the observations. The probable mechanism in this case is clearly one involving only ions in solutions. This means that a substance in a relatively oxidized state must approach the upper end of the graphite body, receive electrons, and depart in a reduced state; the reverse situation will hold at depth.

The pH theory of self-potentials can also be eliminated. This explains the potentials as originating in pH differences in the solutions surrounding the top and the bottom of an ore body. The difficulty here is that no means is available to transfer electrons to or from the ore. pH is a measure of the concentration of hydrogen ion in aqueous solution. If there is no oxidant nor reductant at the electrode, then no charge can be transferred. An exception might be through the formation or decomposition of H_2O or H_2, but this is shown below to be improbable. It should not be inferred that pH is irrelevant, since the actual mechanism may prove to be pH-dependent.

Ranges of Eh and pH in the Zone of Weathering

In this section and the two following, we digress briefly to describe the geochemical environment in which self-potentials originate in terms of oxidation potential and pH. This is necessary because we propose to assign primary significance to the oxidation potential of the solutions surrounding the ore body. The discussions given here are essentially a summary of work under the same project by Sato (1959a). The oxidizing environment is considered first.

The main conclusion of this section may be stated as follows. In the presence of free oxygen, the range of the oxidation potentials of the solutions surrounding a sulfide ore body is set by the reaction,

$$H_2O_2 = O_2 + 2H^+ + 2e^-,$$

$$Eh = 0.682 - 0.0591\ pH + 0.0295 \log \frac{P_{O_2}}{(H_2O_2)}\ \text{volts}, \qquad (9)$$

P_{O_2} refers to the partial pressure of oxygen, (H_2O_2) to the activity of dissolved hydrogen peroxide. When a catalytic agent for the decomposition of hydrogen peroxide is present, this reaction becomes reversible and controls the oxidation potential of an aqueous system in contact with free oxygen. Many elements can act as the catalyst, including iron and manganese which are common in the earth's crust.

The first line of evidence consists of direct measurements of Eh and pH near and within sulfide ore bodies. No published data could be found, so a program was undertaken during 1957 to measure these quantities in both oxidized and primary sulfide ore zones. Data were obtained at the Magma Mine, Superior, Arizona; San Manuel Mine, San Manuel, Arizona; Cole and Campbell Mines, Bisbee, Arizona; and Continental No. One Mine, Big Indian Wash District, Utah.

The technique involved measurements of Eh and pH in underground workings, either in wall and ceiling seepages or in horizontal diamond drill holes. Eh was determined using a platinum electrode, pH using a glass electrode. The reference electrode in each case was saturated calomel, but the data were reduced to the standard hydrogen electrode scale (S.H.E.). A possibility of oxygen contamination of the water was always present. The effect of such contamination would be to increase the Eh values; this implies that the natural, undisturbed values are equal to or lower than the observed values.

The field data are presented in Figure 3. For comparison, the equilibrium oxidation potentials for three half-cell reactions are superposed. The top and bottom lines correspond to the "oxygen-cell" mechanism hypothesized by C. and M. Schlumberger (1922) and Poldini (1938), the oxygen reaction supposedly occurring near the surface and the hydrogen reaction at depth. The oxygen reaction is:

$$2H_2O = O_2 + 4H^+ + 4e^-,\ Eh = 1.23 - 0.0591\ pH + 0.0148 \log P_{O_2}\ \text{volts}. \qquad (10)$$

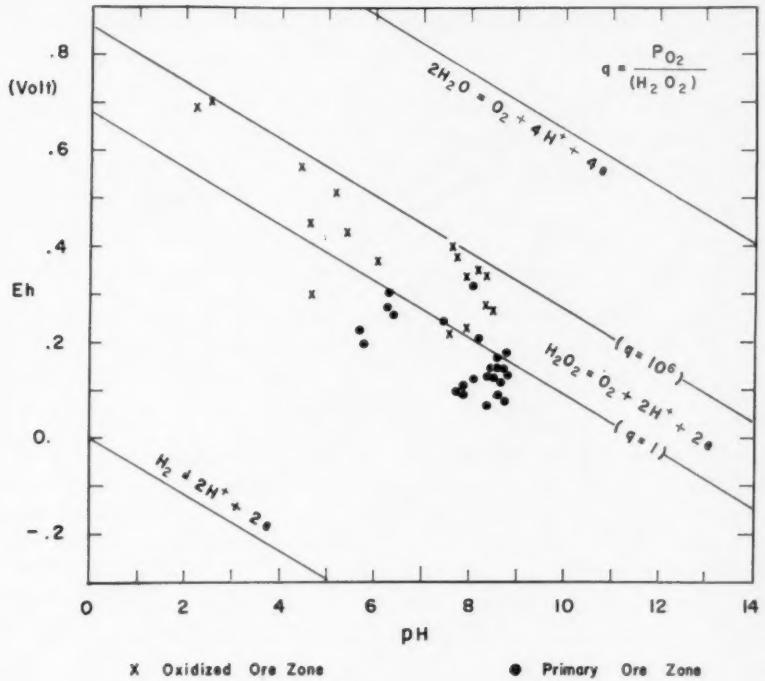

FIG. 3. Eh and pH values of natural waters at the Magma, San Manuel, Cole, Campbell, and Continental No. 1 Mines.

It will be seen that the data strongly contradict this supposition.

Various half-cell reactions were considered in an attempt to explain the observations. The most probable controlling reaction was found to be reaction (9). This reaction is related to the mechanism of the reduction of oxygen; hydrogen peroxide forms as an intermediate product of oxygen reduction. Hydrogen peroxide is not stable and is easily decomposed back to oxygen and water in the presence of a catalyst. The cycle of $O_2 \rightarrow H_2O_2 \rightarrow O_2$ establishes a reversible equilibrium according to equation (10) and controls the Eh value of the system. The hydrogen peroxide activity in natural conditions is uncertain, except that it must be very small. It may be seen that the field data are included within the range 1 to 10^6 for the activity quotient as defined in Figure 3.

Two other lines of evidence tend to confirm the Eh range set by the $O_2 - H_2O_2$ reaction. One is based upon the data taken in lake waters and lake sediments by Allgeir et al (1941); when plotted as in Figure 3, the Eh range appears similarly defined. The other type of data, obtained by Sato (1959a), consists of lab-

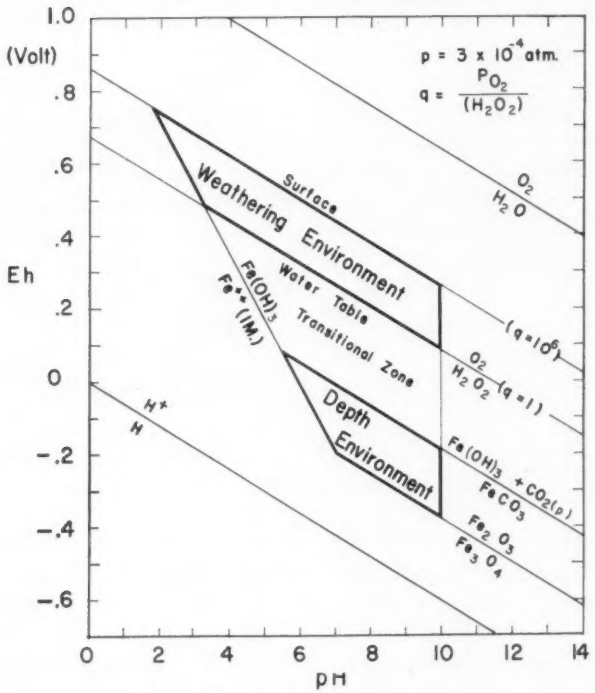

FIG. 4. Deduced Eh-pH conditions in the weathering and depth zones.

oratory oxidation of reduced ferrous and manganous sulfate solutions; curbing of the rates of oxidation was observed within the same potential range.

The range of pH in the zone of oxidation remains to be assigned. Published values range from 4 to 9, with occasional reports as low as 2. The higher values would occur in a limestone area. Consideration of the calcite-water equilibrium without external carbon dioxide partial pressure suggests a maximum value of about 10. The low pH values are usually found in mineralized areas where pyritic ores are actively oxidizing. The normal presence of goethite and limited concentration of dissolved iron in these areas indicate the probable minimum pH value as

$$Fe^{++} + 3H_2O = Fe(OH)_3 + 3H^+ + e^-, \qquad pH^0 = 5.96 - 5.64\ Eh. \quad (11)$$

Figure 4 summarizes the preceding considerations.

Ranges of Eh and pH beneath the Water Table

The field data of Figure 3 do not represent the Eh-pH conditions beneath the water table, due to possible contamination by atmospheric oxygen. We pro-

pose instead to rely on the observed stability of siderite and hematite, together with an assumption of thermodynamic equilibrium. The latter seems plausible on geological grounds.

Siderite is known to occur in unweathered rocks and ores, usually beneath the water table; hence the Eh-pH conditions must fall within the stability field of siderite. This permits us to estimate an upper Eh limit and lower pH limit. Siderite oxidizes to ferric hydroxide:

$$FeCO_3 + 2H_2O = Fe(OH)_3 + CO_2 + H^+ + e^-,$$

$$Eh = 0.614 - 0.0591\ pH - 0.0591 \log P_{CO_2} \text{ volts.} \quad (12)$$

An assumption regarding the partial pressure of carbon dioxide, namely that near the water table it would approach the atmospheric value (3×10^{-4} atm.), reduces the above equation to:

$$Eh = 0.407 - 0.0591\ pH \text{ volts.} \quad (12')$$

To assign a lower limit to pH, we note that reaction (12) does not hold where ferric hydroxide is not stable. Calculations show that siderite dissociates into ferrous ion and bicarbonate ion at the pH given in equation (12). Hence, the same boundary is applicable to both the weathering zone and the depth zone.

The lower limit for Eh is based on the common occurrence of hematite in unweathered rocks and ore deposits. Hematite becomes unstable and is reduced to magnetite below the oxidation potential defined by

$$2Fe_3O_4 + H_2O = 3Fe_2O_3 + 2H + 2e^-, \quad Eh = 0.221 - 0.0591\ pH \text{ volts.} \quad (13)$$

As for the upper pH limit, the equilibrium pH value of the calcite-water system without external CO_2 pressure is also applicable to the depth environment.

Behavior of Sulfide Minerals as Electrodes

Pourbaix's concept of the immunity domain of a metal as defined on an Eh-pH diagram has been discussed earlier. We now examine whether a sulfide mineral possesses such an immunity domain under natural conditions. If so, then it behaves as an inert electrode like platinum, and functions in the self-potential process simply as a conductor of electrons.

For each of the minerals of interest, we find that such an immunity domain exists within the stability field of water; it is restricted by oxidation, reduction, and dissociation reactions. Within this domain, neither active oxidation nor reduction of the mineral occurs, and dissociation equilibrium will be established. Outside of this domain, a tendency exists for oxidation or reduction of the mineral. The electrode potential no longer equals the oxidation potential of the solution, but is determined by the activity of the oxidation or reduction product ion of the mineral in solution. Where a constant removal of the product ion takes place by percolating water, it tends to remain at the boundary value at which the mineral ceases to be inert. The mineral has become unstable and, given enough time, will disappear.

For any mineral, a critical question then arises: does its immunity domain fall within the expected range of natural Eh-pH conditions deduced earlier? If the immunity domain of pyrite, for example, covers the entire Eh-pH range labelled "Weathering Environment" in Figure 4, then we infer that pyrite will assume an electrode potential equal to the oxidation potential of the surrounding solution. Conversely, if it does not, then the oxidation of pyrite will gradually proceed down to the depth where the oxidation potential of the solution nearly equals the upper boundary value of the immunity domain of the mineral.

Sato (1959b) has developed an extensive body of data bearing on the immunity domains of various sulfides. The measurements define the oxidation potential (which may be a function of pH) above which a sulfide tends to be oxidized, or below which it tends to be reduced. In some cases the identification of the reaction was possible by correlation with thermodyamically calculated potentials for assumed electrode reactions. Details of the procedure and discussions of the reaction mechanisms are presented elsewhere. We summarize here the conclusions which are relevant to the present discussion. It may be noted that graphite presents the extreme example of a mineral which is neither oxidized nor reduced within the natural range shown in Figure 4.

In the depth environment, nearly all of the minerals of interest are stable. This is known from geologic observation, and is confirmed by the data of Figure 5. The solid lines define the upper limits of the immunity domains, above which the minerals tend to be oxidized unless coated with insoluble, non-conductive substances. They are based on those theoretical oxidation reactions which most closely match the observations. To illustrate, the oxidation electrode potential of covellite in acid solution agrees with:

$$CuS = Cu^{++} + S + 2e^{-}, \quad Eh = 0.591 + 0.0295 \log (Cu^{++}) \text{ volts.} \quad (14)$$

The upper limit is then obtained by taking the cupric ion activity as 10^{-6}; it is calculated to be 0.414 volt. In basic solution, hydrolysis causes a systematic decrease of cupric ion activity with increasing pH, and the above equation is superseded by the following over-all equation:

$$CuS + 2H_2O = Cu(OH)_2 + S + 2e^{-}, \quad Eh = 0.862 - 0.0591 \text{ pH volts.} \quad (15)$$

In general, the oxidation electrode potentials of sulfide minerals are dependent only upon the activities of the respective metal ions in acid solution, and only upon pH in basic solution. The dashed lines, on the other hand, represent the lower limits of the immunity domains, below which the minerals tend to be reduced. For argentite and covellite, the lines are based on the theoretical reduction reactions which best fit the observations; for example, the measured reduction electrode potential of argentite agrees with:

$$2Ag + H_2S = Ag_2S + 2H^{+} + 2e^{-},$$
$$Eh = -0.061 - 0.0591 \text{ pH} - 0.0295 \log (H_2S) \text{ volts.} \quad (16)$$

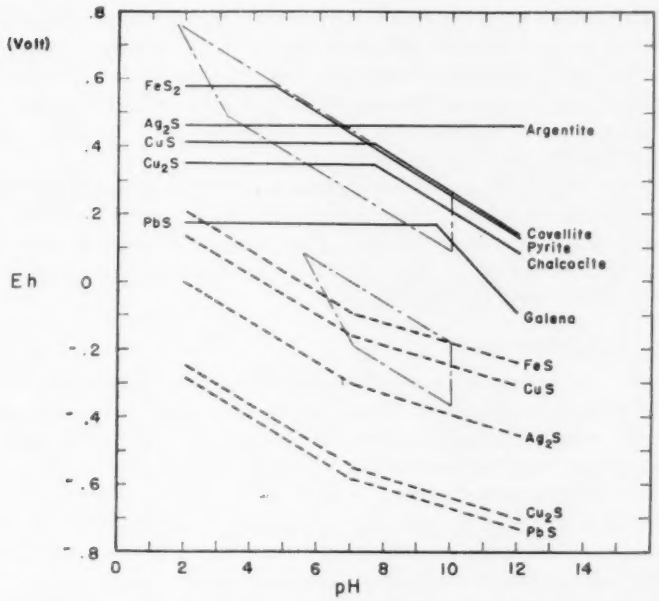

FIG. 5. Experimental upper (solid lines) and lower (dashed lines) boundaries of immunity domains for various sulfide minerals. (Boundaries for weathering and depth environments from Figure 4.)

The lines for chalcocite and galena are based on assumed reactions similar to the above; for pyrite purely experimental values are used. The summation of the activities of the three sulfide ion species, i.e. $(S^{=})+(HS^{-})+(H_2S)$, was chosen as 10^{-6} for the boundary values.

It may be seen that the predicted depth environment is largely within the immunity domains of sulfide minerals, indicating the control of the electrode potentials of the minerals by the Eh value of the surrounding solutions. Figure 5 clearly indicates that oxidation of ore at depth is neither a potential-controlling process nor a current-sustaining process; it indicates the presence of stronger reducing agents than the ore in the surrounding solutions. The control of electrode potential by reduction reaction may appear possible for pyrite and covellite according to the diagram. This may be true, but nevertheless it would be of secondary importance because of the stagnant condition usually prevailing beneath the water table; the total concentration of sulfide ion species, which are reduction products of sulfide minerals, could easily reach a value far exceeding 10^{-6} molal, causing the electrode potentials of the minerals to approach the oxidation potential of the environment. We conclude, therefore, that the electrode potentials of sulfide minerals are primarily controlled by the Eh values of the surrounding solutions.

In the weathering environment, on the other hand, considerable differences in reactivity exist among the minerals discussed. The range of Eh-pH values assigned for this environment covers domains of immunity and oxidation for all of these minerals, indicating that they all oxidize here, though with widely varying degrees. Pyrite oxidizes only under intensely-oxidizing acid conditions, whereas galena does so over most of the range.

Since the zone of weathering is a system open to a fresh supply of rain water, the accumulation of the oxidation product ions, and hence the retardation of the oxidation process is generally difficult. The oxidation of a sulfide mineral is expected to proceed to a depth where the Eh value of the solution equals the upper boundary of the immunity domain.

Self-Potential Mechanism

We can now outline the self-potential mechanism. It must involve two electrochemical half-cell reactions, occurring simultaneously at two different locations on the ore-rock interface. Normally one location is above the water table, the other below, with the ore forming a continuous structure between. The two half-cell reactions must be opposite in nature, one cathodic and the other anodic, involving gain or loss of electrons by substances in solution. The process taking place above the water table is a reduction reaction for the dissolved substances; an oxidation reaction occurs below the water table.

The potential difference which produces the natural currents arises from the difference in Eh (oxidation potential or redox potential) of the solutions in immediate contact with the ore body at the two locations. The substances in solution exist in relatively oxidized states above the water table, and in reduced states below; the difference in the degree of oxidation appears as the difference in Eh, and causes the electric current flow in the presence of a bridging electronic conductor. The ore serves as this conductor. Electrons are transferred through the ore from the reducing agents at depth to the oxidizing agents near the surface; thus the former are oxidized and the latter reduced.

The ore body itself cannot directly participate in the electrochemical reaction which yields self-potentials. To do so, it would be necessary to oxidize the ore under reducing conditions and to reduce it under oxidizing conditions. So far as the self-potential mechanism is concerned, the ore body functions as a chemically inert medium for the transport of electrons.

If the ore body is neither oxidized nor reduced by the surrounding solutions, then the maximum potential difference available for producing natural currents may be inferred from Figure 4. The Eh and pH values of the depth environment may be taken at the center of the indicated domain, $pH = 8$ and $Eh = -0.15$ volt. For the weathering environment, we will assume $pH = 4$ and relatively intense oxidation (upper boundary of the domain). The difference in Eh is then 0.78 volt. This figure should be applicable to graphite.

If the ore body is subject to oxidation by the surrounding solutions, then the

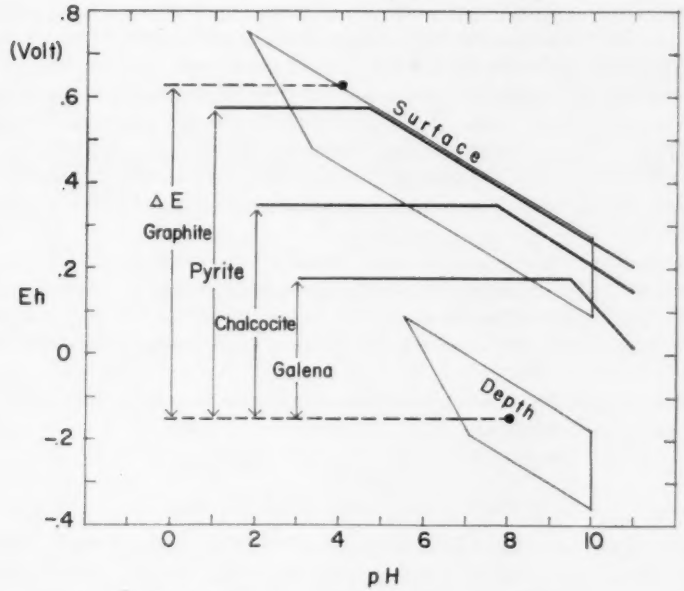

FIG. 6. Maximum available potential differences for various ores.

maximum potential difference is reduced by an amount which corresponds to the difference between the upper boundary value of Eh for the weathering environment and that of the immunity domain for the ore mineral. The weathering processes active near the surface remove the ore from the system, either by dissolving it or by coating it with insoluble, nonconductive substances, down to the depth where the Eh of the solution equals the potential at which the ore starts to oxidize. The latter potential is presumably very close to the upper boundary value for the immunity domain of the ore where leaching process is active. In the depth environment, on the other hand, active reduction of the ore is improbable, and the Eh values of the surrounding solutions are directly available, as the ore acts as an inert electronic conductor. Hence, the above average Eh value for the depth environment should be applicable to all ore types. The maximum potential difference available for the production of natural currents is then given as the difference between this Eh value and the upper boundary value for the immunity domain of a sulfide mineral. This point is illustrated with examples in Figure 6. The potential differences for several minerals are.

Graphite	0.78 volt
Pyrite	0.73 volt
Covellite	0.57 volt
Chalcocite	0.50 volt
Galena	0.33 volt

To identify the half-cell reactions which are responsible for the natural cur-

rents, two criteria are relevant: first, the elements involved must be abundant in nature (at least near the ore body); second, the reactions must be able to take place within the Eh range expected in natural conditions.

In the zone of weathering, reduction reactions for free oxygen and ferric ion are the most probable ones. The control of the oxidation potential for this environment by the reduction reaction of oxygen to hydrogen peroxide was discussed previously. The reaction and the potential are given in equation (10). Hydrogen peroxide is unstable and quickly decomposed by catalytic elements in solution.

Dissolved iron in this environment exists as both ferric ion and ferrous ion. The reduction of ferric ion to ferrous ion proceeds according to equation (8). The ferrous ion produced at the ore-electrolyte boundary will be oxidized to ferric ion by free oxygen, and will thus repeatedly be utilized for the production of the current.

Where cupric ion is abundant under mildly acid conditions, the reduction of cupric ion to cuprite Cu_2O,

$$2Cu^{++} + H_2O + 2e^- = Cu_2O + 2H^+,$$
$$Eh = 0.203 + 0.0591\ pH + 0.0591 \log (Cu^{++}), \qquad (17)$$

may play a role in the self-potential mechanism. The reduction of cupric ion to cuprous ion or native copper is probably not important, because of low potentials for the reactions. The presence of manganese oxides may have a secondary effect on the mechanism, as they act as oxidizing agents for ions in solution.

Beneath the water table, the oxidation reactions for ferrous ion, ferrous hydroxide, and bisulfide ion are most probable ones. The oxidation of ferrous ion to ferric hydroxide proceeds according to equation (11). At pH = 8, and ferrous ion activity of 10^{-3} M. (about 0.056 grams per liter), the equilibrium potential for this reaction is given as -0.18 volt.

The oxidation of ferrous hydroxide to ferric hydroxide in over-all effect may be expressed as

$$Fe(OH)_2 + H_2O = Fe(OH)_3 + H^+ + e^-, \qquad Eh = 0.2715 - 0.0591\ pH. \quad (18)$$

At pH = 8, the Eh value is given as -0.20 volt.

The oxidation of HS^- ion is complex, but its oxidation potential in weakly basic solution is more or less similar to the above two Eh values. An uncertainty exists as to the abundance of HS^- ion in deep-circulating water, hence the significance of this reaction for the self-potential mechanism is somewhat questionable.

The occurrence of the above half-cell reactions requires adjustment of electrical balance of ions in the solutions, since electrical neutrality must be maintained by the solutions. The half-cell reactions taking place near the surface proceed toward the addition of electrons to the solution, causing an increase in the total negative charge. It becomes necessary either to add positive ions to or remove

negative ions from the solution. A reverse situation exists at depth; either removal of positive ions or addition of negative ions is required.

The above requirement is fulfilled by the net movement of positive ions toward the top of an ore body, and that of negative ions toward the deeper portion, which complete a closed electric circuit involving:

Solution (below) | Ore (below)→(electrons)→Ore (above) | Solution (above)

(Positive ions) — — →

← — — (Negative ions)

Practically all naturally occurring ions can participate in the ionic conduction, although considerable variations may exist as to the extent of the contribution. Relative abundance and ionic mobility are probably the major factors which influence the extent. Hydrogen ion and hydroxyl ion are most favored in this respect. It is not necessary for each ion to travel all the way along the path of conduction; only the directional movement of ions is important. Positive ions and negative ions moving in opposite directions may collide with each other and form neutral molecules before they cover a small fraction of the conduction path. A succession of such minute conduction segments serves just as well to the passage of electric currents, so long as the general direction of the ionic movement is maintained.

We suggest that the ferrous ion—ferric ion couple and the hydrogen peroxide-oxygen couple are most probable half-cell reactions participating in the self-potential mechanism above the water table; the ferrous ion—ferric hydroxide couple and, to a lesser extent, the ferrous hydroxide—ferric hydroxide couple are most probable ones below. Directional movements of ions in the pore solutions provide the means of passage for electric current within the country rocks. Hydrogen ion and hydroxyl ion are probably most important in this ionic conduction mechanism. The process is sketched in Figure 7.

GEOLOGIC IMPLICATIONS

Based on the proposed mechanism, four geologic conditions are required to produce self-potentials. First, the ore body must be a good conductor of electricity; this implies electronic rather than electrolytic conduction. Second, the ore must provide a nearly continuous connection between ground waters of differing oxidation potential. Third, the ore must be chemically stable or inactive with respect to the oxidation potentials of the solutions with which it is in contact. Fourth, no permanent insulating films can form on the surface of the ore.

Several inferences can be drawn, concerning the expected occurrence of self-potentials. One relates to the mineral types which may produce them; graphite and most of the common iron and copper sulfides satisfy the above conditions. Sphalerite fails owing to its low conductivity. Galena often occurs as separate masses with no electrical connection between, and in addition forms a protective

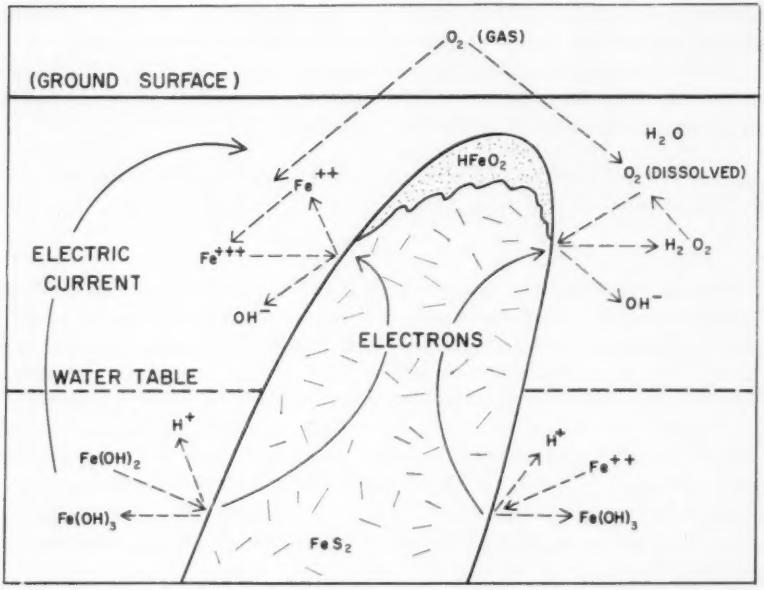

FIG. 7. Proposed electrochemical mechanism for self-potentials.

coating of lead sulfate or carbonate which effectively prevents the half-cell reactions. The iron hydroxides are poor conductors.

The maximum potential difference available for the production of electric currents depends upon the chemical stability of the mineral. Values for five minerals were estimated in an earlier section. Further experimental work is required to extend the work to other minerals of commercial importance. The maximum potential difference appears to be about 0.8 volt, for stable minerals such as graphite and pyrite.

The distribution of equipotentials about the ore body is a related problem, but it will not be treated in this paper; one aspect is considered in a companion paper (Mooney and Sato, in preparation). Since all lines of the electric current must begin and end on the ore body, it would appear that the maximum anomaly to be expected in a self-potential survey would be one-half of the total potential difference. This assumes a reference point at infinity. The largest anomalies should be of the order of 400 mv. We are unable to account for reported anomalies of a volt or more, except by assuming unusual chemical conditions or superposition of other potentials unrelated to the ore body.

A disseminated or impregnated ore body may produce self-potentials if the spacing between mineral grains is small. At every junction between electronic and electrolytic conductor, the mode of transfer of electricity must be changed. If the solution between adjacent particles is maintained uniform, then the trans-

fer will be effective. Failure to achieve this will introduce a concentration gradient and a consequent voltage drop, which is likely to occur where the distance between the ore grains is large. From these considerations, we conclude that the magnitude of self-potentials will rapidly diminish as the intensity of ore impregnation becomes less.

In arid country, self-potentials are expected to be small. Low water table and deep oxidation are common in a desert region. A large portion of the potential drop occurs in the vicinity of the top of unoxidized ore, which lies at considerable depth. Further, the ground moisture may be inadequate to support the half-cell reactions. Finally, electric current flowing through a rock of normal moisture content may encounter a layer of low moisture content. A critical condition will occur when the high resistance of the layer blocks out the passage of electric current through the rock.

An arctic region is not favorable for self-potentials. The low ground temperature retards the rates of chemical reactions. Permafrost and other frozen layers impede the ionic conduction greatly. Tundra vegetation and high water table tend to maintain a reduced condition even in the vicinity of the surface.

The electrochemical mechanism for self-potentials does not specifically depend upon the existence of a water table, nor upon a continuous band of mineralization extending above and below. It is quite possible that the requisite contrast in oxidation potential may exist under other circumstances. However, the water table provides the unusually favorable condition of a large and abrupt contrast. We believe that most significant self-potential anomalies will prove to be associated with the water table. From this, Brant's (1955) conclusions would follow, that self-potentials would be severely inhibited where the ore existed completely beneath the stationary ground water surface (such as a swamp) or beneath permafrost. A rising ground water level would also reduce self-potentials, whereas a slowly falling level should increase them. Self-potential exploration in underground mines appears to lack promise, since oxidation potential would vary slowly from place to place except in the immediate vicinity of the cut-surface.

ACKNOWLEDGMENTS

This report is based upon a theoretical and experimental study of the electrochemistry of sulfides, carried out at the University of Minnesota under U. S. Atomic Energy Commission contract AT(05-1)-719. For helpful discussions concerning the subject matter treated in this paper, grateful acknowledgment is made to Drs. R. M. Garrels, Z. Z. Hugus, T. R. Madden, and G. M. Schwartz. Valuable cooperation in field work was provided by staff members of the Grand Junction Operations Office of the U. S. Atomic Energy Commission, Magma Copper Company, San Manuel Copper Corp., and Copper Queen Branch, Phelps-Dodge Corporation.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 250–274, 15 FIGS.

THE USE OF ACOUSTIC LOGS IN THE EVALUATION OF SANDSTONE RESERVOIRS*

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ABSTRACT

It is shown that acoustic velocities in sandstones are primarily dependent on porosity, shaliness, and pressure differential between overburden and fluid pressures. Although there are undoubtedly other variables which have some effect on acoustic velocities in sandstones, usable porosity predictions can be made from acoustic borehole logs if measured velocities are corrected for effects of pressure differential and shaliness.

A theoretical relation between acoustic velocity and pressure differential in a hexagonal packing of spheres has been empirically extended by correlation of laboratory measurements on cores with actual well-bore measurements. A system of empirical relations among acoustic velocity, porosity, and self potential of sandstones is developed. Further, it appears that the resistivity of water in permeable rocks can be estimated from the velocity and resistivity of adjoining shales. When this is possible, the SP log can then be used to estimate the shaliness of a sandstone in order to correct velocities for porosity estimates.

INTRODUCTION

The adequate evaluation of a sandstone hydrocarbon reservoir requires reasonably precise estimates of porosity and water saturation. Borehole and laboratory data show that acoustic velocities in sandstones are primarily dependent on porosity, pressure differential between overburden and reservoir fluid pressures, and shaliness. Therefore, porosity estimates relatively independent of reservoir fluid content can be obtained from acoustic logs provided that adequate corrections for pressure differential and shaliness can be made. A simple empirical relation between pressure differential and depth can often be found. An empirical technique for employing the self-potential log to account for shaliness has been found, but quantitative use of the SP log requires a knowledge of formation water resistivity. This necessity prompted the investigation of possible relations among formation water resistivity, acoustic velocity, and formation resistivity in shales. Obviously, estimates of formation water resistivity are also necessary for deducing the water saturation of potential hydrocarbon-bearing sandstones. From the above empirical relations and previously published information, a system for estimating porosity, water resistivity, and degree of shaliness has been evolved and tested by comparison with core data and recovered water resistivities. These tests were carried out for cases representing a wide range of physical and geological variables.

Since the system to be described yields estimates of water resistivity and shaliness, it follows that all of the factors necessary to calculate formation water saturation are available, given a measurement of formation resistivity. Thus, usable estimates of both porosity and water saturation can be made from a combi-

* Manuscript received by the Editor July 6, 1959.

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nation of acoustic velocity, resistivity, and self-potential logs alone, whether the sandstone is shaly or not.

The remainder of this paper consists of the description of the proposed interpretation system and is divided into the following sections:

1) Determination of the basic variables affecting acoustic velocities in nonshaly sandstones from a review of laboratory data.

2) Derivation of an empirical relation so that usable estimates of porosity in nonshaly sandstones can be made.

3) Derivation of a technique for using the SP log to correct observed velocities for shaliness.

4) Development of an empirical equation for estimating connate water resistivity (needed for quantitative use of the SP log in Step 3 and for calculating water saturation).

5) Comparison of porosities and water resistivities predicted by the proposed system with core porosities and recovered water resistivities.

PRIMARY FACTORS WHICH AFFECT VELOCITIES IN NONSHALY SANDSTONES

Some of the first significant data on sandstone velocities were published by Wyllie, et al (1956). Wyllie's data (Figure 1) consisted of laboratory measurements of velocities[1] and porosities of sandstone cores which had been air-saturated (curve 3) and water-saturated (curve 2) at room conditions. A few additional measurements were made on water-saturated samples under "higher pressures" (curve 1). Results of these laboratory measurements showed that (1) velocities

[1] Unless otherwise noted, the term "velocity of" shall be taken to mean "velocity of sound in."

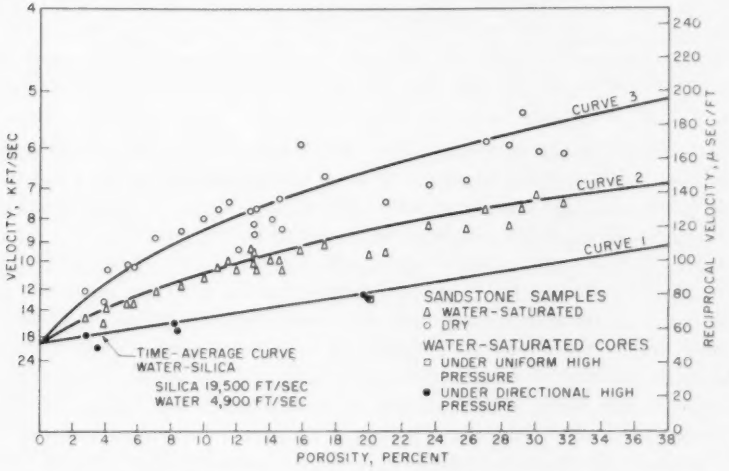

FIG. 1. Velocity vs Porosity for Sandstone Cores (after Wyllie, et al, 1956.)

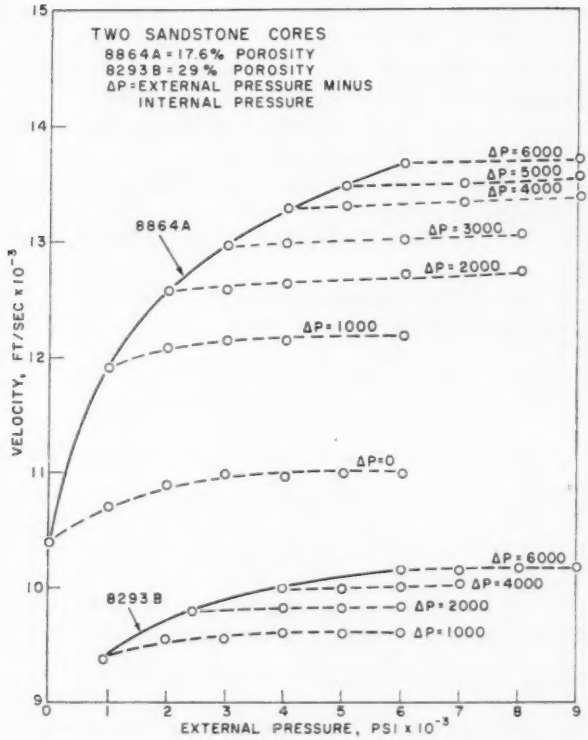

FIG. 2. Laboratory Measurements of Two Sandstone Cores Showing Acoustic Velocity as a Function of the Difference between External and Internal Pressures (after Hicks, et al, 1956).

of water-saturated samples are higher than those of air-saturated samples at room conditions, (2) velocities of air- or water-saturated samples are a function of porosity, the velocity decreasing with increasing porosity, and (3) velocities of water-saturated sandstones increase with increasing pressure.

Figure 2 shows the results of laboratory experiments by Hicks, et al (1956), which clarified the effects of pressure distribution on the velocity of two sandstone cores. In these experiments, a pressure differential ΔP was generated by exerting one pressure on the core jacket ("external pressure") and a different pressure on the fluid in the pores ("internal pressure"). The core-jacket pressure was transmitted to the grains making up the sandstone, so that ΔP represented a pressure differential between average pressure on the matrix grains and pore-fluid pressure. As the average pressure on the matrix is related to intergrain pres-

sures, ΔP is also related to the pressure differential between intergrain and fluid pressures.

Hicks' measurements (see Figure 2) showed that velocities in sandstones are dependent on such a pressure differential. The experiments further indicated that, for practical purposes, the velocity is constant for a constant pressure differential, regardless of "external" pressure. The effects of laboratory-generated pressure differential on velocities in sandstones are of interest because an analogous pres-

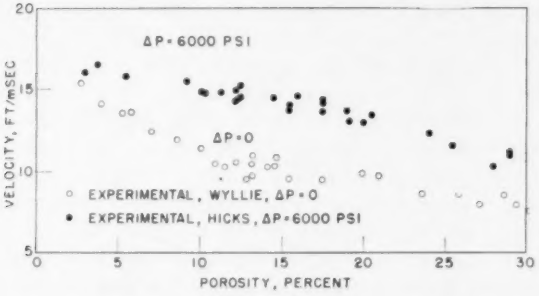

FIG. 3. Laboratory Measurements of Sound Velocities in Water-Saturated Sandstone Cores, $\Delta P = 0$ and $\Delta P = 6{,}000$ psi.

sure differential should exist between overburden and fluid pressures on in-situ rocks.

Hicks also ran a series of similar velocity experiments on water-saturated sandstone cores under a pressure differential of 6,000 psi. From a comparison (see Figure 3) of Hicks' data ($\Delta P = 6{,}000$ psi) with Wyllie's data at room conditions ($\Delta P = 0$), it is apparent that pressure differential effects on velocity cannot be ignored (if velocities are to be used for porosity prediction), provided the laboratory experiments are representative of pressure differential effects in-situ.

Wyllie, et al (1958) subsequently performed experiments at similar pressure differentials on sandstone cores (Figure 4) which confirmed Hicks' results between 0 and 30 porosity percent and which also extended the experimental velocity-porosity relation to higher porosities (up to 75 porosity percent). Limited data in these experiments also indicated that replacement of water by oil or air when the cores were under high pressure differentials had only a small (of the order of one or two percent) effect on the measured velocities.

Thus, it could be concluded from the experimental data that velocities in sandstones (1) decrease with porosity under all pressure differentials, (2) increase with increasing pressure differential, (3) decrease significantly at zero pressure differential when water in the pore system is replaced by air, and (4) decrease by less than about three percent of the water-saturated velocity at pressure differ-

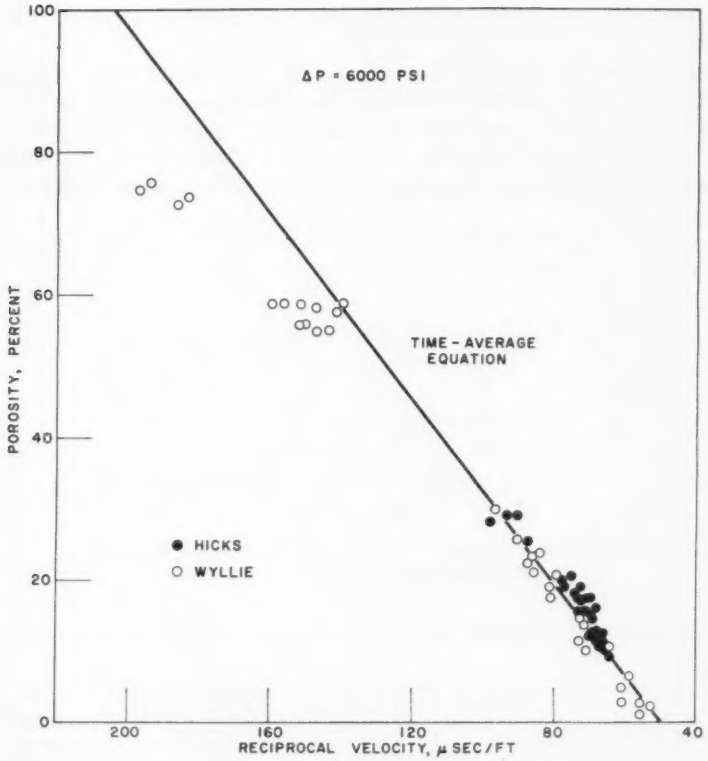

FIG. 4. Laboratory Measurements of Sound Velocities in Water-Saturated Sandstone Cores Expressed as Reciprocal Velocity vs Porosity; $\Delta P \approx 6{,}000$ psi for Entire Porosity Range.

entials of 4,000 psi or more (for a porosity of 20 percent) when water in the pore system is replaced by oil.

In terms of using velocity measurements for porosity prediction in sandstones, the experimental data mean that velocity of sound in sandstones is a function primarily of porosity and pressure differential at higher pressure differentials. At lower pressure differentials, it appears that the type of fluid content might also have a detectable effect on velocity, especially for higher porosities.

To describe the reciprocal velocity-vs-porosity relation at high pressure differentials, Wyllie, et al (1956, 1958) proposed the "time-average" equation for water-saturated rocks,

$$\frac{1}{v} = \frac{1}{v_a}(1 - \phi) + \frac{1}{v_f}\phi, \tag{1}$$

where $1/v$ is reciprocal velocity of sound in the sandstone, $1/v_s$ is reciprocal velocity of sound in a solid body made up of matrix material, $1/v_f$ is reciprocal velocity of sound in the fluid in the pores (in this case, water), and ϕ is fractional porosity. The time-average reciprocal velocity, $1/v$, is meant to represent a maximum or "terminal" velocity of sound in rocks under higher pressure differentials (of the order of 6,000 psi). Laboratory determinations indicate that $1/v_s$ for solid quartz is around 50 μ sec/ft and that $1/v_f$ for water is close to 205 μ sec/ft; if these figures are taken for $1/v_s$ and $1/v_f$, respectively, the linear relation shown in Figure 4 between reciprocal velocity and porosity is obtained. It can be seen that this time-average function is a good representation of experimental measurements at a pressure differential of 6,000 psi for the usual practical porosity range of 0 to 30 percent. The time-average function fails to represent the experimental points at higher porosities for rocks under 6,000 psi pressure differential. However, a more serious shortcoming of equation (1) is that it does not predict what happens for cases falling between the "terminal" velocities of higher pressure differentials and the much lower velocities obtained at room conditions.

In this regard, a theory proposed by Gassman (1951) for sound propagation through hexagonal packings of spheres is of interest because it predicts a dependence between pressure differential and velocity. Since Gassman's theory is for an ideal model (perfect hexagonal packing of equal-radius spheres, fixed porosity, no cementing effects, etc.), a considerable amount of empirical modification is to be anticipated before an equation of the form derived by Gassman will fit data for actual rocks.

DERIVATION OF EMPIRICAL EQUATION

Gassman's equation for a hexagonal packing of equal-radius spheres is

$$\rho v^2 = \left[\frac{1}{c_s(1-\phi) + c_f\phi - 4c_s^2\tilde{c}}\right](1 - 8c_s\tilde{c})^2 + 16\tilde{c}, \tag{2}$$

where

$$\tilde{c} = \frac{1}{24\sqrt{2}}\left[\frac{18\pi(1-2\delta)^2}{c_s^2(1-\delta^2)^2}\Delta P\right]^{1/3}, \tag{3}$$

and

$$\rho = \rho_f\phi + \rho_s(1-\phi). \tag{4}$$

c_f is fluid compressibility, c_s is solid (rock matrix material) compressibility, δ is Poisson's ratio for the solid material, ρ_f and ρ_s are the fluid and solid densities, respectively, and ΔP is the pressure differential existing between rock frame and fluid content.

In analogy to equations (2), (3), and (4) we decided to consider an empirical

equation of the form

$$\rho v^2 = [1 + q_s(1 - \phi)]\left[\frac{(1 - 8c_s\bar{c})^2}{c^* - 4c_s^2\bar{c}} + 16\bar{c}\right], \tag{5a}$$

where ρ is bulk density, c^* is bulk compressibility, ϕ is fractional porosity, v is velocity, c_s is matrix material compressibility,

$$\bar{c} = \frac{5(1 - \phi)^4}{24\sqrt{2}}\left[\frac{18\pi(1 - 2\delta)^2}{c_s^2(1 - \delta^2)^2}\Delta P\right]^{1/2}, \tag{5b}$$

and

$$q_s = \frac{2(1 - 2\delta)}{1 + \delta}. \tag{5c}$$

This system of empirical equations, hereafter referred to as "the empirical equation," was chosen to meet the following requirements:

1) A fractional power pressure dependence between velocity and pressure differential similar to that in Gassman's equation would be incorporated.

2) The magnitude of the pressure differential term would decrease with increasing porosity (suggested by experimental data).

3) The velocity predicted at $\phi = 0$ should approximate laboratory measurements on velocities in quartz crystals.

4) The velocity predicted at $\phi = 1.0$ should approximate the velocity of sound in water.

5) The values of the constants c_s, c_f, ρ_s, ρ_f, and δ should be compatible with published values.

6) The velocity-porosity relation should agree with laboratory measurements of Hicks at $\Delta P = 6{,}000$ psi and of Wyllie at pressure differentials approaching zero.

In accordance with condition (5), the values $\delta = 0.149$ (approximate Poisson's

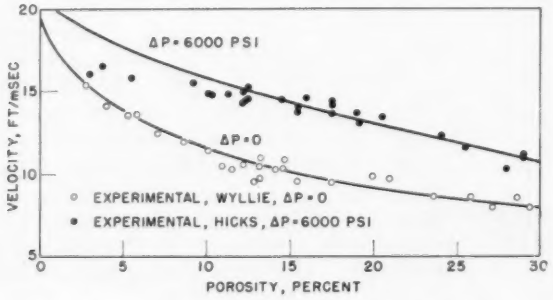

FIG. 5. Comparison of Empirical Equation with Core Data.

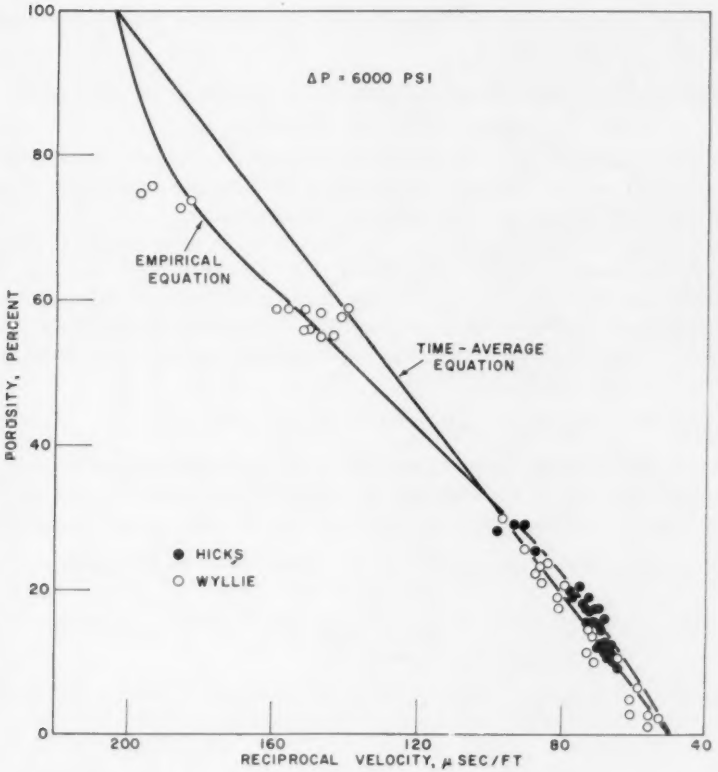

FIG. 6. Comparison of Empirical Equation with Core Data and Time-Average Equation.

ratio of silica), $c_s = 2.5 \times 10^{-12}$ cm²/dyne (approximate compressibility of silica), $c_f = 45.3 \times 10^{-12}$ cm²/dyne, $\rho_s = 2.70$ gm/cm³, and $\rho_f = 1.0$ gm/cm³ were substituted in equations (5). When ΔP is set equal to zero, equations (5) predict a velocity-porosity curve which agrees with Wyllie's data (Figure 5, lower curve), and when ΔP is set equal to 6,000 psi, the upper curve of Figure 5 is obtained. Calculations show that conditions (1), (2), (3), and (4) are also satisfied.

Equations (5) can also be compared with the data more recently published by Wyllie at higher pressure differentials and high porosities (Figure 6).

Equations (5) can be used to calculate families of velocity-porosity curves for other pressure differentials. Such calculations predict that the increase in velocity at a fixed porosity with increase in pressure differential becomes smaller at higher pressure differentials. Above 5,000 or 6,000 psi, the increase becomes insignificant

as far as practical porosity predictions from the empirical equation are concerned.

DERIVATION OF CORRECTIONS FOR EFFECTS OF SHALINESS ON VELOCITIES MEASURED IN THE BOREHOLE

Derivation of an empirical equation which correctly correlates experimental measurements does not guarantee that usable porosity predictions can be obtained from borehole acoustic logs under in-situ conditions.

Comparison of the empirical equation with borehole measurements requires first that the pressure differential ΔP be related to a measurable quantity. Experience to date has indicated that porosity can be predicted with sufficient precision if the pressure differential of the empirical equation is replaced by a factor proportional to depth. A factor which is apparently appropriate in the Gulf Coast and Four Corners areas is

$$\Delta P(\text{in psi}) = 0.6 \times \text{depth (in ft)}. \tag{6}$$

Figure 7 shows one of the first comparisons between reciprocal velocities from an acoustic log and core porosities for the corresponding intervals in an 11,000-ft Gulf Coast well. The solid curve is the reciprocal velocity-vs-porosity curve

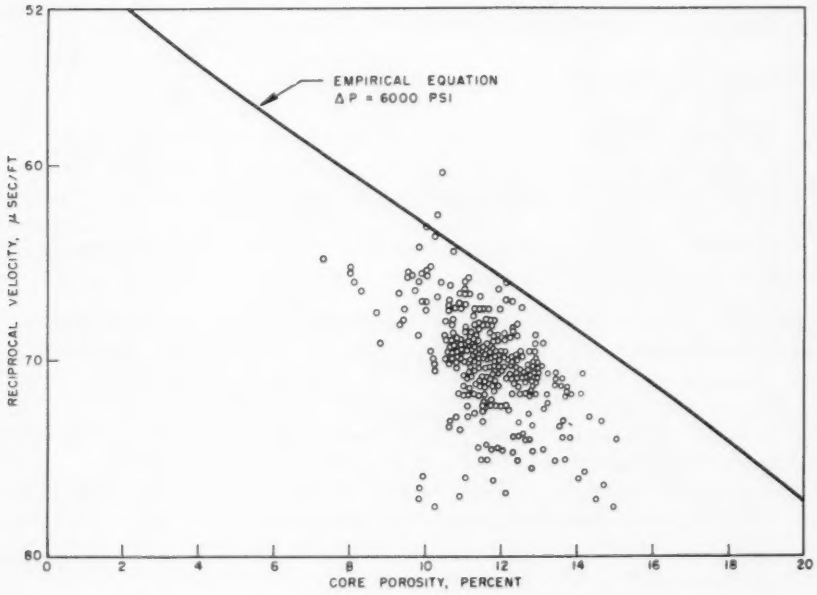

FIG. 7. Reciprocal Velocity from Acoustic Log vs. Core Porosity, Sand and Shale Series (10,445–10,995 ft), Gulf Coast.

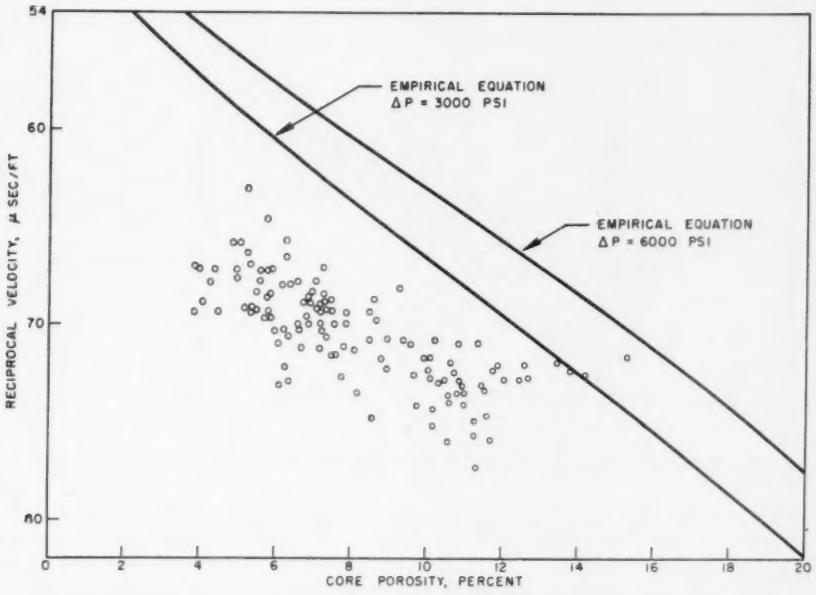

FIG. 8. Reciprocal Velocity from Acoustic Log vs. Core Porosity, Four Corners Area.

predicted by equations (5) for the pressure differential (6,000 psi) applicable at this depth. It is obvious that acceptable porosity predictions are obtained from the empirical equation for only the points representing higher velocities at a given porosity.

Figure 8 is a similar comparison for a shaly sandstone reservoir at about 5,000 ft in the Four Corners area ($\Delta P = 3{,}000$ psi). For comparative purposes, the 6,000-psi curve shown on Figure 7 is also shown on Figure 8. Although there is a general shift of data points in the direction predicted by the empirical equation for the decrease in depth between these two reservoirs, the Four Corners example leads to the same conclusion that was obtained in the Gulf Coast example—the empirical equation predicts reasonable porosities only for the higher velocities at a given porosity.

Since the empirical equation correctly correlated the laboratory data, it was apparent that some factor not previously considered was affecting the borehole measurements. An examination of core data and available logs indicated that the points on Figures 7 and 8 deviated more and more from the appropriate empirical curve as the degree of shaliness of the zone increased.

The effect of shaliness is demonstrated qualitatively in Figure 9, where total SP is plotted versus reciprocal velocity for intervals with a constant porosity.

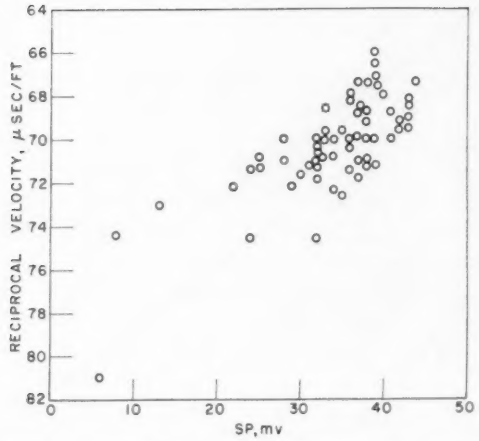

FIG. 9. Reciprocal Velocity vs SP, Gulf Coast Example (11 Percent $<\phi<$12 Percent).

The effect of shale on the borehole measurements is manifested by a decrease in both the SP and the velocity. This shows that velocities in sandstones are also a function of shaliness.

Since shaliness apparently affects both the self-potential and the acoustic logs, it should be possible to correct the acoustic log for effects of shaliness by using self-potential logs.

Figure 10 shows the plot of reciprocal velocity vs porosity obtained when

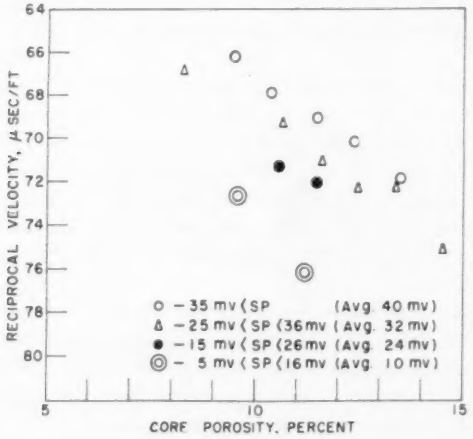

FIG. 10. Reciprocal Velocity vs Core Porosity as a Function of SP Deflection, Sand and Shale Series (10,445–10,995 ft), Gulf Coast Example.

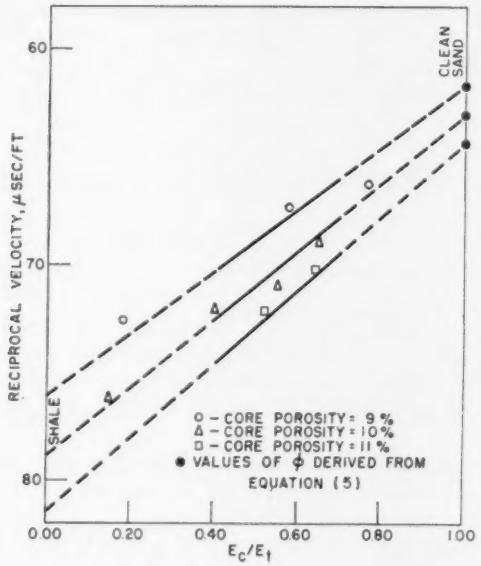

FIG. 11. Sand-Shale Sections, E_c/E_t vs Reciprocal Velocity as a Function of Porosity, $\Delta P = 6{,}000$ psi.

the points of Figure 7 are averaged by 1-porosity-percent increments and 10-mv self-potential increments. It can be seen that these average points for the sands in the Gulf Coast example define a family of reciprocal velocity-vs-porosity curves, where each member of the family represents a restricted self-potential range.

Figure 11 presents some of the same data in a more usable form. In Figure 11, the self-potential deflections have been converted to values of E_c/E_t, where E_c is the electrochemical potential computed from the SP log and E_t represents the corresponding E_c for a perfectly "clean" sand computed from the relation

$$E_t = 65 \log \left[\frac{R_{mf}}{R_w} \right]. \tag{7}$$

This relation was derived from electrochemical-potential data published by Hill and Milburn (1956). E_c is obtained by correcting the observed SP for effects of electrokinetic potential and bed thickness.

It was noted that the points of Figure 11 indicated a family of linear relationships between the reciprocal velocity and E_c/E_t, each line representing a particular value of porosity. The intersections of each line with the ordinate represented by $E_c/E_t = 1.0$ and by $E_c/E_t = 0$ should define the values of reciprocal

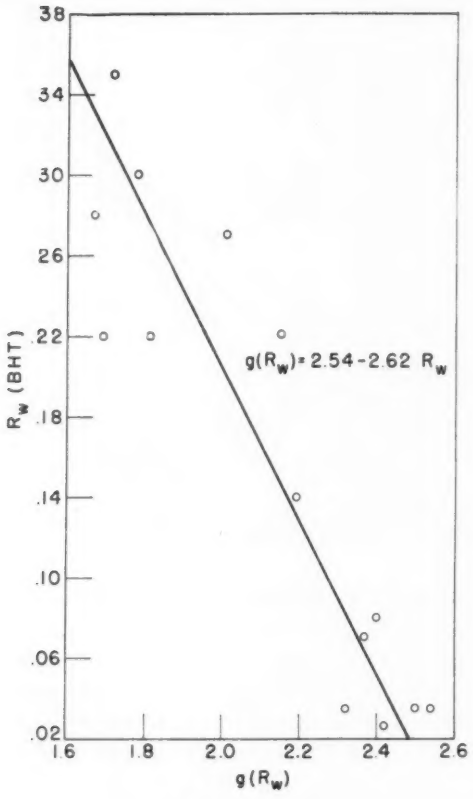

FIG. 12. $g(R_w)$ vs R_w.

velocity of clean sand and shale, respectively, for the porosity represented by the line.

The clean-sand reciprocal velocities and porosities predicted by the Gulf Coast data were found to agree with the values obtained from the empirical equation derived previously at a ΔP of 6,000 psi. Similarly, the Four Corners data agreed with the empirical-equation velocity-vs-porosity values for a ΔP of 3,000 psi (Figure 8). This suggests that the empirical equation can be used to establish the clean-sand end points for any pressure differential.

Extrapolation of the straight lines represented by Four Corners data (at 5,000 feet) to the shale end points showed that the shale "porosity"—reciprocal velocity points changed very little from those obtained in the Gulf Coast example (at 11,000 ft). This implies that the reciprocal velocity-porosity curve for shales may not change with depth.

These results provided the following means of constructing interpretation charts similar to Figure 11 for depths of interest:

1) From equation (6), depth (z) was converted to pressure differential (ΔP).

2) The ΔP calculated in step (1) was substituted into equations (5), and corresponding values of reciprocal velocity and porosity were calculated for clean sandstone.

3) On the horizontal axis of the chart, values of E_c/E_t from 0 to 1.00 were marked.

4) On the vertical axis, represented by $E_c/E_t = 1.00$ (clean sand), the values of reciprocal velocity ($1/v$) and porosity (ϕ) calculated in step (2) for the porosity range of interest were marked.

5) On the vertical axis, represented by $E_c/E_t = 0$ (shale), values of the reciprocal velocities and porosities of interest defined by Figure 11 were marked (e.g., $1/v = 78.9$, $\phi = 10$ percent; $1/v = 76.1$, $\phi = 9$ percent; etc.).

6) Straight lines were drawn between the clean-sand and shale end points for each porosity.

A set of charts (Figures 13–15) constructed in this manner for pressure differentials of 1,000 psi, 3,000 psi, and 6,000 psi is included in Appendix I.

These charts can be used in the following manner to obtain porosity estimates:

1) Compute E_t for the applicable R_{mf} and R_w from equation (7).

2) Calculate E_c from the observed self-potential deflection from the shale base by applying corrections for electrokinetic potential, etc.

3) Calculate E_c/E_t, taking care to correct either E_c or E_t to the temperature of the other.

4) Estimate pressure differential in psi (ΔP) by multiplying depth in feet by 0.6, or another such factor proved appropriate by experience.

5) Using the chart for the applicable ΔP, plot reciprocal velocity, $1/v$, from the acoustic log versus the E_c/E_t calculated in step (3), and read porosity. An example of porosity determination by this method is given in Appendix I.

A comparison of porosities computed in this manner with core values will be given later. It should first be noted, however, that use of equation (7) requires a knowledge of mud filtrate resistivity R_{mf} and connate water resistivity R_w. Of course, the usual procedure in log analysis is to use the SP to estimate R_w. In the present case, we wish to use the SP as a measure of shaliness, so an independent means of obtaining R_w is desirable.

CALCULATION OF CONNATE WATER RESISTIVITY FROM RESISTIVITY AND ACOUSTIC LOGS

Inspection of acoustic and resistivity logs has indicated that surprisingly consistent relations exist among acoustic velocity in shales, resistivity in shales, and connate water resistivity in adjacent strata. The resistivity of a shale is dependent on the resistivity of the contained fluid, and in a normal stratigraphic sequence the fluid contained in a shale must be in some state of equilibrium with the con-

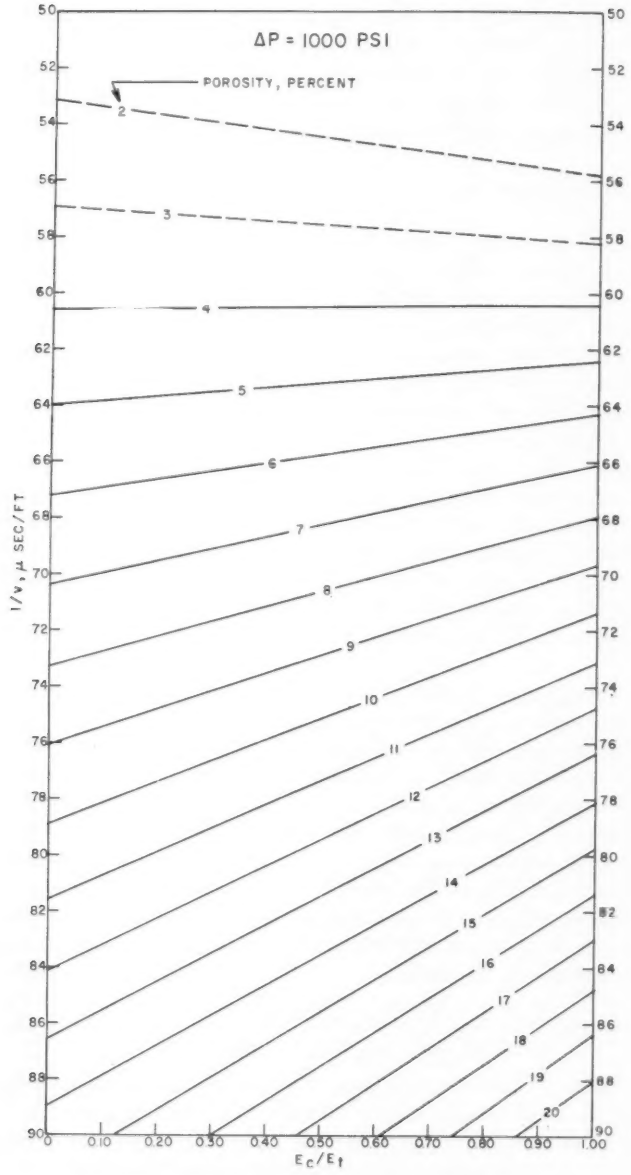

FIG. 13*a*. E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 1{,}000$ psi.

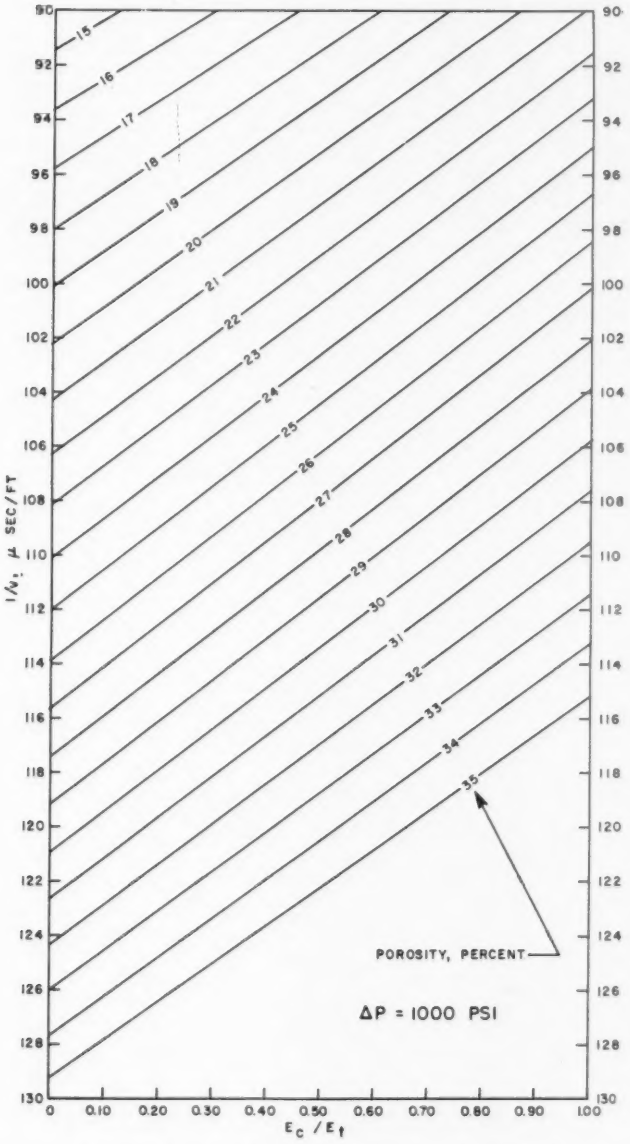

FIG. 13*b*—E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 1{,}000$ psi.

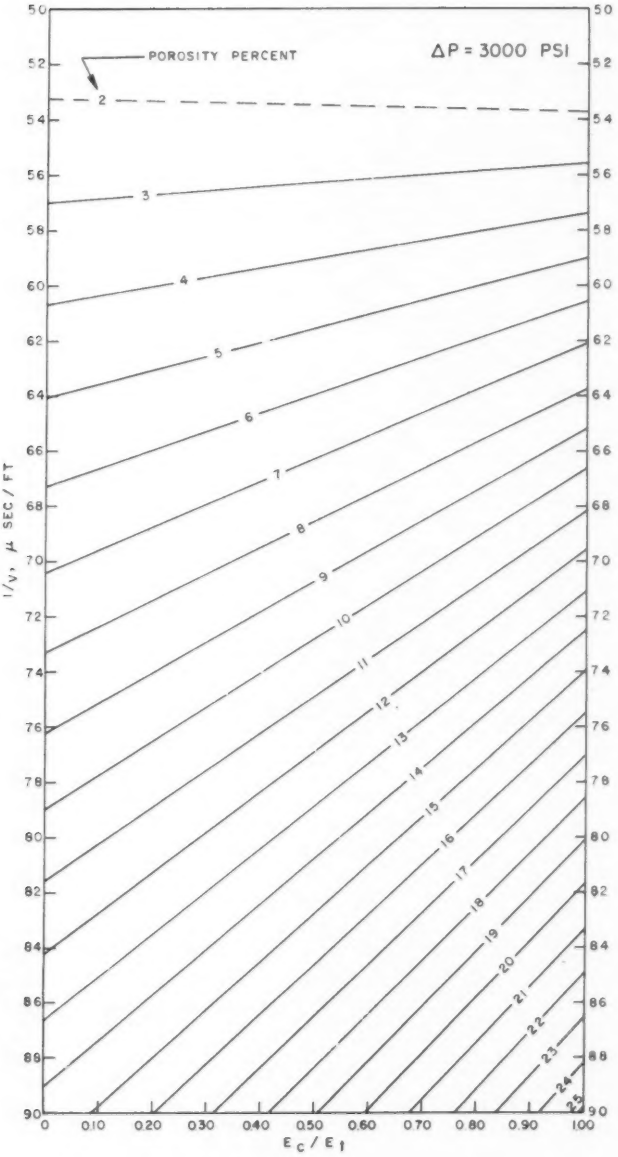

FIG. 14a. E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 3{,}000$ psi.

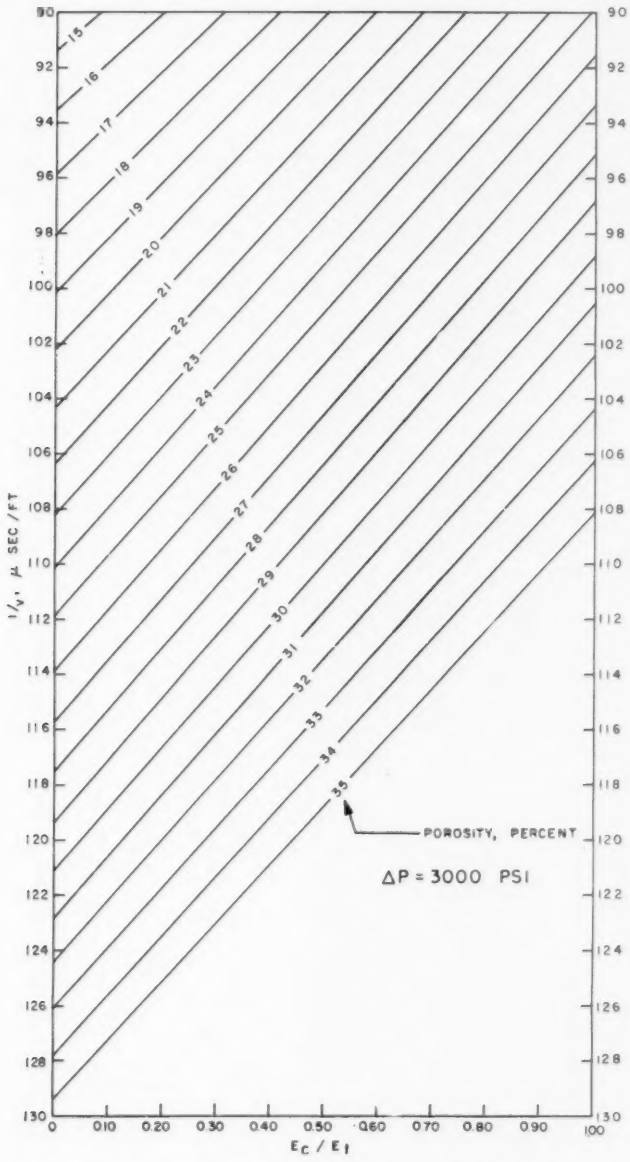

FIG. 14*b*. E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 3{,}000$ psi.

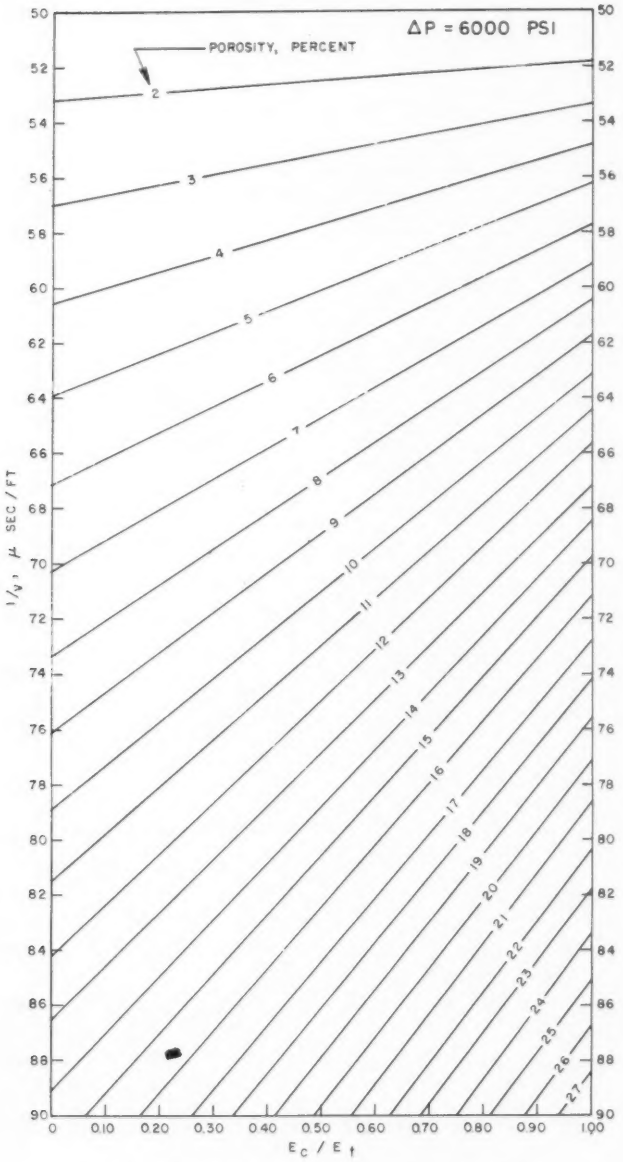

FIG. 15*a*. E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 6{,}000$ psi.

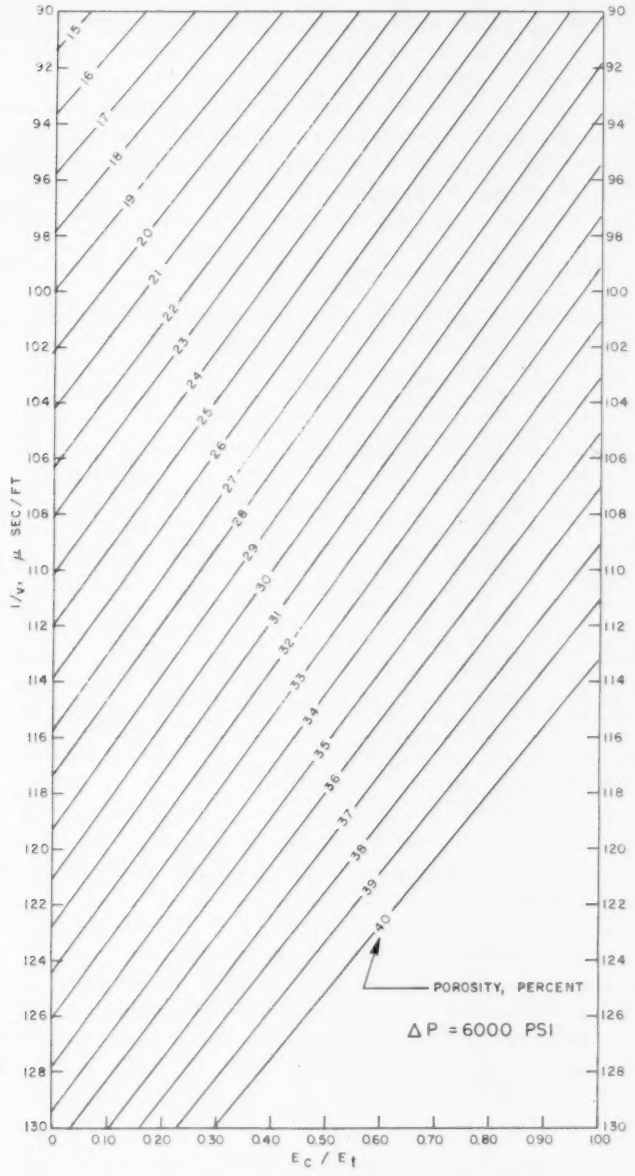

FIG. 15*b*. E_c/E_t vs $1/v$, Sand-Shale Sections, $\Delta P = 6{,}000$ psi.

nate water in adjacent permeable strata. Therefore, the possibility of using velocity and resistivity in shales for estimating connate water resistivity of adjacent permeable strata was explored.

The following steps outline the procedure used. Seventeen test cases were carefully selected from available data to insure that the resulting comparisons would be as conclusive as possible. The following restrictions were placed on the intervals selected for the comparison:

1) Sample descriptions and logs indicated that the zone was unquestionably a shale.

TABLE 1

DETERMINATION OF WATER RESISTIVITY FROM RESISTIVITY AND ACOUSTIC LOGS

No.	Age	Formation	Depth ft	R_{sh} ohm-m	$1/v$ μ sec/ft	R_w ohm-m BHT*	R_{we} ohm-m BHT*
1	Cretaceous	Cardium sandstone	5,550	17	78.3	0.30	0.310
2	Cretaceous	Peace River sandstone	7,076	8	84.0	0.22	0.450
3	Cretaceous	Peace River sandstone	6,864	6	93.9	0.22	0.090
4	Mississippian	Banff sandstone	2,290	10	83.8	0.28	0.385
5	Mississippian	Banff sandstone	2,583	4	114.0	0.27	0.283
6	Devonian	D_2 carbonate	4,073	3	103.9	0.066	0.078
7	Mississippian	Turner Valley carb.	4,575	12	93.2	0.22	0.207
8	Cretaceous	Gething sandstone	2,970	5	102.0	0.14	0.170
9	Devonian	Beaverhill Lake carb.	10,075	13	84.4	0.08	0.110
10	Cretaceous	Bullhead sandstone	3,825	5	99.0	0.14	0.110
11	Cretaceous	Gething sandstone	1,700	6	110.0	0.23	0.267
12	Devonian	D_3 carbonate	5,552	5	91.0	0.03	0.050
13	Miocene	D sand	9,526	0.75	120.0	0.035	0.038
14	Devonian	D_2 carbonate	7,346	54	61.0	0.023	0.019
15	Devonian	D_2 carbonate	7,205	120	57.5	0.035	0.022
16	Cretaceous	Gallup sandstone	5,900	10	90.0	0.35	0.200
17	Oligocene	Vicksburg sandstone	11,115	2.8	88.0	0.056	0.020

* Borehole temperature.

2) The resistivity logs showed no evidence of invasion.

3) The shale was within the same formation and close to the permeable strata from which the water was recovered.

4) The fluid recovery was conclusive.

5) The acoustic log was reliable in the shale selected.

The seventeen available cases which met these requirements are listed in Table 1. It should be noted that the cases considered represent a wide range in geologic age, formations, lithologies,[1] geographic locations, depths of burial, and fluid resistivities. As a result, any conclusions derived from the following comparisons should be representative of a wide range of conditions commonly encountered in practice.

[1] Although the remainder of this paper is restricted to sandstone interpretation, it appears that the proposed method for predicting R_w may be extended to carbonates.

A resistivity equation similar to that more commonly applied to clean sands was considered:

$$\log R_{sh} = \log R_w - g(R_w) \log \phi_{sh}, \tag{8}$$

where R_{sh} is resistivity of the shale, R_w is resistivity of water in an adjacent sand (assumed to be in equilibrium with that in the shale), ϕ_{sh} is "porosity" of the shale, and $g(R_w)$ is some function of R_w. From equation (8),

$$g(R_w) = \frac{\log (R_{sh}/R_w)}{-\log \phi_{sh}}. \tag{9}$$

From equation (9), $g(R_w)$ was calculated for each of the seventeen test cases. R_{sh} was taken from the resistivity log, R_w was that recovered on test from adjacent permeable formations (at borehole conditions), and ϕ_{sh} was calculated from the velocity log with the $1/v$-vs-ϕ relation defined by the $E_c/E_t=0$ ordinate of Figures 13–15.

The function $g(R_w)$ was plotted against R_w (Figure 12). From this plot, the empirical equation

$$g(R_w) = 2.54 - 2.62\ R_w \tag{10}$$

was derived. When equation (10) is substituted in equation (8), the following expression is obtained:

$$\log R_w + 2.62 R_w \log \phi_{sh} = \log R_{sh} + 2.54 \log \phi_{sh}. \tag{11}$$

Equation (11) can be solved for R_w by using ϕ_{sh} calculated from the acoustic log and R_{sh} from the resistivity log. The R_w calculated for each of the test cases is shown as R_{wc} in Table 1.

It can be seen that the values of R_w so determined compare well, in general, with the resistivity at borehole conditions of the recovered water. It should be noted, however, that equation (11) has a serious shortcoming. Differentiation shows that the function

$$F(R_w) = \log R_w + 2.62 R_w \log \phi$$

is double-valued, since

$$\frac{dF(R_w)}{dR_w} = \frac{\log_{10} e}{R_w} + 2.62 \log \phi,$$

or

$$\frac{dF(R_w)}{dR_w} = 0 \quad \text{for} \quad R_w = \frac{-0.434}{2.62 \log \phi}.$$

Thus, there are two values of R_w which will satisfy equation (11), one greater than and one less than the value $-0.434/2.62 \log \phi_{sh}$. The two R_w's are usually

sufficiently different for there to be no problem in determining which one is correct.

COMPARISON OF CALCULATED POROSITIES WITH CORE POROSITIES

Several comments regarding the method of porosity determination discussed above are in order. First, it is obvious that the linear trends between $1/v$ and E_c/E_t are based on a limited amount of core data. Second, the shale "porosity"-vs-reciprocal velocity relation is based on *extrapolation* of available data, not on *measured* porosities and velocities. Third, the method is based on the assumption that the values of SP are not affected by additional factors (e.g., suppression by hydrocarbons). Because of these qualifications, it must be expected that the method will be subject to refinements as results of its application are accumulated. However, in those cases where core porosities have been available for comparison, trials of the method have so far indicated that porosities can be predicted with usable precision.

Porosities calculated from these charts have been compared with core-analysis porosities from approximately 1,000 ft of cores representing over 70 intervals. The calculated porosities were within ± 1 porosity percent of the core porosities for 40 percent of the 70 cases tested, within ± 2 porosity percent for 80 percent of the cases, and within ± 3 porosity percent for 90 percent of the 70 cases tested. The 1,000 ft of cores represented intervals of all degrees of shaliness from wells in Bisti field, New Mexico; Javelina field, Texas; Sheridan field, Texas; and Bayou Sorrel field, Louisiana. The porosities ranged from 5 to 30 percent, and the depths ranged from 5,000 to 11,000 ft.

CONCLUSIONS

Experimental data and comparisons of borehole measurements with core analyses show that acoustic velocities in sandstones are primarily dependent on (1) porosity, (2) pressure differential between average matrix and pore-fluid pressures, and (3) shaliness.

Acoustic velocities in sandstones are also dependent on fluid content. However, this effect apparently decreases to minor proportions as the pressure differential increases to values corresponding to depths of most reservoirs.

Although there are undoubtedly other variables which have some effect on acoustic velocities in sandstones, usable porosity predictions can be made from acoustic borehole logs if measured velocities are corrected for effects of pressure differential and shaliness.

A theoretical relation between acoustic velocity and pressure differential in a hexagonal packing of spheres has been empirically extended to correlate the experimentally defined relations among velocity, pressure differential, and porosity for nonshaly sandstones. It has been found that the assumption of a constant proportionality between pressure differential and depth provides a usable means of accounting for pressure differential effects on velocity.

Shaliness can be accounted for by use of the self-potential log.

Porosity estimates based on these correction schemes for pressure differential and shaliness have been found to be within ± 1 porosity percent of core porosities about 40 percent of the time, within ± 2 porosity percent about 80 percent of the time, and within ± 3 porosity percent about 90 percent of the time.

It appears possible to calculate usable values of connate water resistivity in permeable strata by using velocities and resistivities recorded in adjacent shales. An empirical technique has been tested for seventeen cases representing a wide range of conditions where conclusive water recoveries were available for comparison. The technique generally predicted water resistivities with acceptable accuracy, but it should be considered subject to refinement.

ACKNOWLEDGMENT

The author thanks the management of Shell Development Company for permission to prepare and present this paper. The author also gratefully acknowledges the computational work by Mr. M. E. Talbot upon which the conclusions reached in the paper are based.

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APPENDIX I

POROSITY CALCULATION FROM ACOUSTIC AND SP LOGS

Introduction

Figures 13–15 present the relation between E_c/E_t and reciprocal velocity $(1/v)$ for a constant porosity (ϕ). (E_c is the actual electrochemical potential, and E_t is the theoretical total electrochemical potential for perfectly clean sand.) These charts were constructed as outlined in the text.

The porosity-reciprocal velocity relation for $E_c/E_t = 1.0$ (clean sand) is given by equations (5) of the text. Equations (5) describe the relations among velocity, porosity, and pressure differential. Because of the dependence of the clean-sand porosity-velocity relation upon pressure differential, interpretation charts must be constructed for each pressure differential of interest. Figures 13–15 include charts for pressure differentials of 1,000, 3,000, and 6,000 psi, corresponding to depths of 1,700 to 10,000 ft.

Example Calculation, 4,877–4,488 Feet, Four Corners Area

1) From the electrical survey, SP = 37 mv and $R_t = 55$ ohm-m.

2) From equation (6), $\Delta P = 0.6z = 0.6 \times 4{,}880 \approx 3{,}000$ psi.

3) The estimated $E_k = 3$ mv, the observed E_c (borehole temperature) = SP $- E_k = 34$ mv, or E_c (77°F.) = 31.5 mv.

4) From equation (7), $E_t = 70.3$ mv at 77°F. for $R_{mf} = 3.4$ ohm-m at 77°F., $R_w = 0.31$ ohm-m at 77°F. (R_w calculated from equation 8 of the text).

5) $E_c/E_t = 31.5/70.3 = 0.45$.

6) From the acoustic log, $1/v = 72.4$ μ sec/ft.

7) For $E_c/E_t = 0.45$ and $1/v = 72.4$ μ sec/ft, the chart for $\Delta P = 3{,}000$ psi (Figure 14) indicates a porosity of 9.6 percent.

GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 275-282, 8 FIGS.

MARINE SEEP DETECTION—A NEW RECONNAISSANCE EXPLORATION METHOD*

H. F. DUNLAP,† J. S. BRADLEY,† AND T. F. MOORE†

ABSTRACT

A number of major oil accumulations of the world are associated with oil or gas seeps. At the least, seeps prove the existence of mobile hydrocarbons in a basin. At the most, and when used with other geological and geophysical data, they can aid in locating exploratory wells.

An effective and inexpensive instrumental technique for locating gas seeps has been developed for use in water-covered areas. If a seep is present, some of the methane dissolves in the water as the gas bubbles rise to the surface. Currents spread this methane-enriched water into a long plume. A boat samples the water continuously, operating over a grid laid out at right angles to the current. The gas dissolved in the water is broken out of solution, and trace concentrations of methane detected using an infrared analyzer. This equipment has detected seeps at distances as great as six miles. A novel system of locating using navigational radar is used in carrying out the survey.

Several marine seeps surveys have been carried out using equipment mounted on various vessels ranging in size from a 14-ft outboard powered skiff to a coastwise freighter. Under most circumstances, the cost of the survey is a few cents per acre. In new basins, the method promises to be of considerable value in localizing areas of interest for more expensive exploration methods.

Seeps have been known since before recorded history. How much oil has been discovered by drilling on seep information is debatable, but it is certainly large. DeGolyer (1940, p. 21) stated, "Direct indications (of gas and oil) are positive evidence of the occurrence of oil or gas in the subsoil, though not necessarily in commercial quantities, and their occurrence first attracted the attention of the prospector to most of the important oil regions and many of the important oil fields of the world." Link (1952) estimated that at least half of the world reserves were discovered by drilling on or near seeps.

The early history of the oil industry in this country is replete with instances of discoveries made directly as a result of drilling on or near seeps. Drake's first successful well at Titusville, Pennsylvania, was located near an oil seep. Many of the major salt dome discoveries of the Gulf Coast in the early 1900's resulted from drilling near oil or gas seeps.

Table 1 lists a few of the major oil fields of the world which are closely associated with oil or gas seeps. The discoveries shown here were made by visual observation of seeps without the benefit of modern instrumentation. This paper describes a technique for instrumental detection of gas seeps in water-covered areas, which brings this branch of the oil finding technology up to date.

By "seep," we mean oil or gas present in sufficient quantities to appear as a distinct phase at the surface. This is in contrast to some geochemical techniques in which evidence of petroleum is sought from trace amounts of hydrocarbons absorbed in soil samples.

* Presented at the twenty ninth Annual International Meeting, November 12, 1959. Manuscript received by the Editor September 25, 1959.

† The Atlantic Refining Company, Dallas, Texas.

TABLE I

SOME MAJOR OIL FIELDS ASSOCIATED WITH SEEPS

Field	Country	Cumulative Production
		(Millions of barrels)
West Columbia	U. S.	128
Mene Grande	Venezuela	474
La Paz	Venezuela	533
Bolivar Coastal	Venezuela	6,300
Infantes	Columbia	180
Masjid I Sulaiman	Iran	1,110
Gach Saran	Iran	185
Kirkuk	Iraq	1,500
Burgan	Kuwait	2,800
Bahrain	Bahrain	207
Baku	Russia	Large

A possible explanation of the rather marked correlation of seeps with producing areas is that the earth is much more severely faulted and fractured than most people realize. Evidence is presented in a paper by Blanchet (1957) that on the average about 15 lineal miles of faults per square mile would be found in basin areas. This degree of fracturing would be expected to provide more than adequate communication with subsurface reservoirs. We conclude from the above that location of gas seeps, which are in effect a direct indication of the occurrence of mobile hydrocarbons, should assist the exploration of new petroleum provinces.

The principle of marine seep detection is that seep gas, principally methane, rising as bubbles from the sea bottom to the surface, will be partially dissolved in the water. The water with dissolved gas will be spread by currents into a plume of gassy water, extending downcurrent from the seep. To locate these plumes, water samples are taken continuously on lines run perpendicular to the current

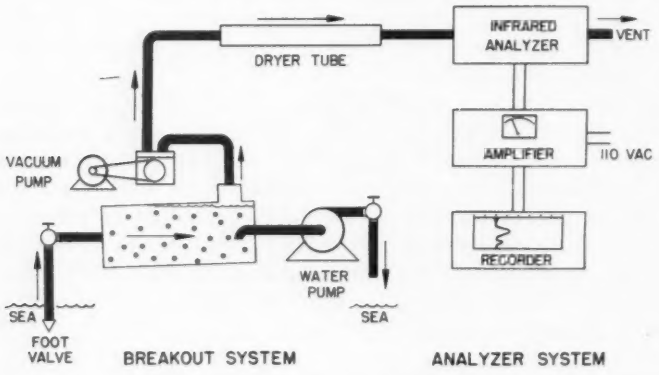

FIG. 1. Flow diagram—seep detection unit.

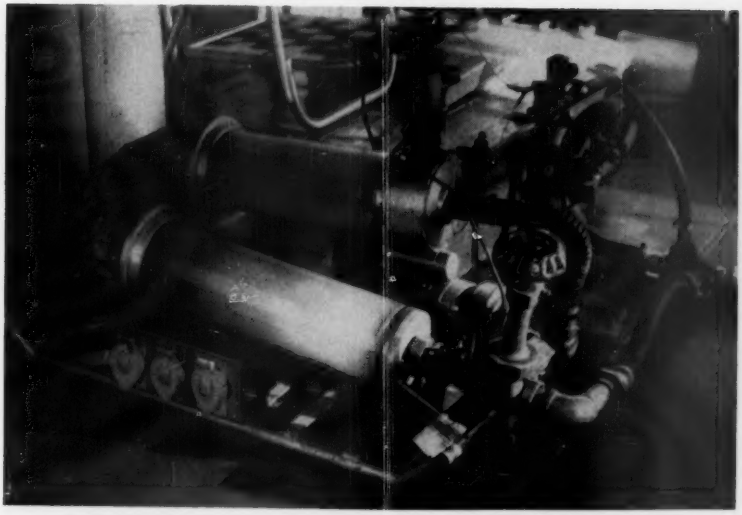

FIG. 2. Gas breakout unit.

direction. The water is degassed, and the gas broken out of water is analyzed for methane.

The instrumentation (Figure 1) consists of the breakout system, which degasses the water sample and pumps the gas to an analyzer system which produces a record showing the methane concentration. Water samples are drawn continuously into the vacuum chamber, where dissolved gasses are broken out. The water level is controlled by intake and exhaust values. The water pump draws the degassed water from the vacuum chamber and returns it to the sea. The vacuum pump maintains a high vacuum in the chamber and passes the gasses broken out of the water to the flow control at a pressure slightly above atmospheric. The gas from the breakout system is dried, filtered, and the flow measured before passing to the analyzer. Facilities for calibration, using gas of known methane concentration, and for zero checking, using atmospheric air, are provided in the flow control equipment. The analyzer system consists of a nondispersive infrared gas analyzer sensitized to methane, together with the associated electronic equipment and recorder. Figures 2 and 3 are photos of a typical installation of the gas breakout unit and of the infrared analyzer plus auxiliary equipment.

The analyzer is the heart of the seeps detection instrumentation and is sensitive enough to detect one part per million of methane in air. In practice, the usable sensitivity is determined by the system noise level which is a function of

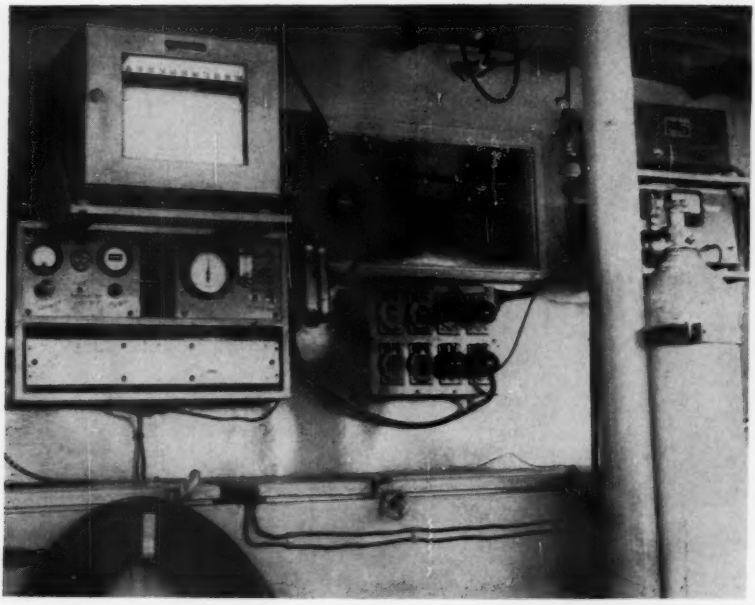

FIG. 3. Infrared analyzer and associated equipment.

many operating variables. Our experience indicates that usable sensitivities of a few parts per million are usually attainable.

Figure 4 shows the results of some control tests run in Corpus Christi Bay, Texas, using artificial seeps leaking methane at 30 cu ft per hour, and at one cu ft per hour from a depth of about 9 ft. Figure 4 shows the areal distribution of methane concentration as determined by several traverses across the plume of gassy water, together with the concentration of methane in gas from the breakout unit as a function of the distance downstream from the seeps along the line of maximum gas concentration. In this area, the background value of methane dissolved in the water was as high as 50 parts per million of methane (probably due to producing activities carried on in the vicinity). In spite of this background, Figure 4 shows that seeps of this type can be picked up at considerably more than one mile from the point of gas escape. Later experience obtained in carrying out surveys indicated that the plume of water from actual seeps can sometimes be detected at distances as great as six miles. In general, the distance at which a seep can be detected will depend upon the amount of gas escaping, the water currents which occur, the variation in the background level of methane dissolved in water, and the noise level of the detection system.

For seep surveying, a grid is run on one-mile spacing across the prevailing cur-

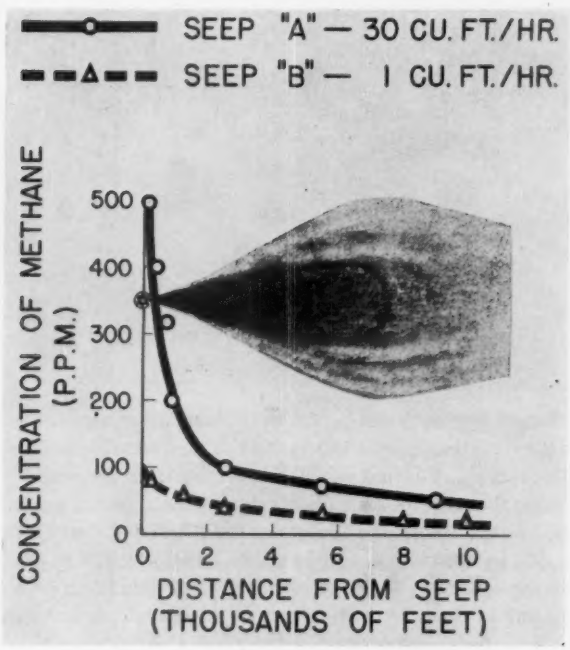

FIG. 4. Gas concentration near artificial seeps.

rents. Radar navigation has been used to maintain a predetermined course in areas where the survey does not extend more than 20 to 30 miles from land. In carrying out this navigation technique, a navigational radar with 2, 4, 8, 16, and 32 mile ranges is used with transparent charts of the coastline prepared to match the scale of the radar range selected. When the transparent chart is matched with the radar picture, the boat position is the center of the screen. This system has proved both practical and economical. Where good targets are available on the shoreline, positions can be located to better than a quarter of a mile at a 32-mile range. At smaller ranges the accuracy is proportionately better.

It is sometimes difficult to maintain courses perpendicular to the currents as the currents may vary radically in short distances. Where currents are highly variable, it may be necessary to run lines spaced closer than one mile in order to insure adequate coverage.

A position fix is taken at each gas indication on the initial grid survey. These are revisited at a later date for confirmation and localization to distinguish genuine seeps from gas indications which may be due to variations in gas content of the water due to water interfaces, high and variable background, or other transi-

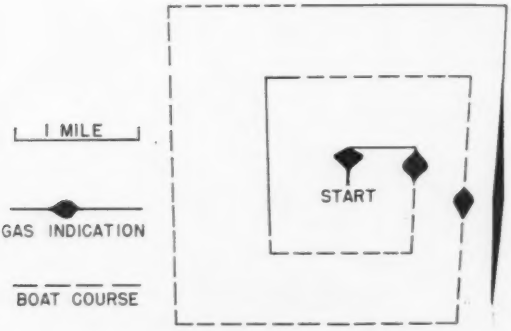

FIG. 5. Detail grid around a seep.

ent phenomena. A true seep will persist in the same location, with the plume trailing in different directions as the currents shift. Sea conditions will normally preclude the observation of actual gas bubbles rising from the seep.

In localizing the seep, an expanding square pattern is run around the location (marked by a buoy) where the indication was first noted. Figure 5 shows the results obtained in one such detailed survey. This grid was run using a compass course and measuring elapsed time along each leg, allowing for drift as determined from the bearing of the buoy. The plume of gassy water from the seep is clearly shown.

The density of seeps has been observed to vary widely and has ranged from

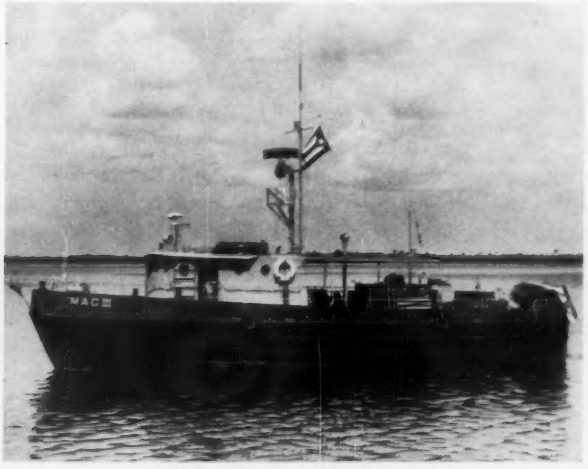

FIG. 6. Diesel powered, 65 ft boat used in offshore work.

FIG. 7. Outboard powered barge used in shallow protected waters.

two confirmed seeps in 3½ million acres to 16 confirmed seeps in about 25 thousand acres. Both of these surveys were carried out in areas which by other classifications looked promising. The fact that very few seeps were found in the 3½ million-acre plot does not condemn this block, of course, but we believe that most explorationists would be impressed by the thousandfold greater density of seeps in the smaller block.

The speed of the survey is controlled by the boat speed which, in turn, may be reduced by adverse weather. Survey speeds average about 10 knots. In a 12-hour day, 10 hours on the grid, 85,000 acres can be covered. Assuming 20 operating days per month, 1.7 million acres could be covered in the initial grid each month. If equal times are required for running the initial grid and for confirmation of the indications (plus lost time due to breakdown and weather), about 850,000 acres per month can be surveyed.

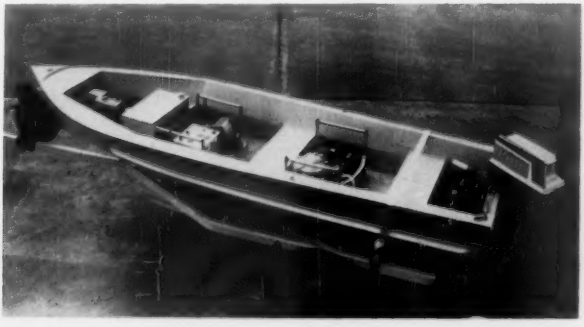

FIG. 8. Seep detecting equipment mounted in 14 ft outboard powered skiff for use in rivers and lakes.

Boats used for marine surveying have ranged from a diesel-powered, 65-ft, steel crew boat for offshore operations (Figure 6) to a 22-ft outboard-powered barge which has been used in protected bay waters (Figure 7). The equipment is compact enough to mount in a 14-ft outboard-powered skiff for use in inland lakes (Figure 8).

In summary, a technique for detection of gas seeps in water-covered areas has been developed and proven operational in a number of surveys in domestic and foreign waters. The technique is capable of inexpensively exploring large areas for reconnaissance purposes. The seep indications found should be useful in delineating those portions of the area surveyed for further exploratory work.

It is a pleasure to acknowledge the encouragement and interest of Mr. W. Dow Hamm and the assistance of Messrs. R. L. Slobod, C. H. H. ter Kuile, J. R. Gunter, C. A. Youngman, P. L. Bowling, and others who have worked on this project.

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GEOPHYSICS, VOL. XXV, NO. 1 (FEBRUARY, 1960), PP. 283–311, 17 FIGS.

SEISMIC DATA ENHANCEMENT—A CASE HISTORY*

R. J. GRAEBNER†

ABSTRACT

The theory relating to many methods—for example, multiple seismometer techniques—which the geophysicist may control to improve record quality is well known. However, its application has not been fully exploited. An example of the reduction of theory to practice in one area characterized by poor records is presented. It comprises a series of analytical tests designed to discover the cause of poor records, to examine the effect of each variable on the signal-to-noise ratio, and to evaluate the solutions predicted by theory. The tests showed that the poor record quality was attributable chiefly to relatively strong surface and near-surface waves propagating outward from the shot. Wave length filtering by means of suitable shot and seismometer patterns, and compositing through data processing methods, greatly improved record quality and permitted magnetic recording of reflected signals over a broad frequency range. The tests established, in the allotted time, that the quality of the data would meet clearly specified standards of performance.

Experience has shown that better seismic data can generally be obtained when the design of techniques is based on the special character of the signal and noise determined from simple tests rather than when the design is based on general assumptions.

INTRODUCTION

The increasing costs of finding oil compel geophysicists to evaluate more carefully than ever before the ways in which existing exploration techniques may best be utilized. The general subject of setting up standards of performance by which an exploration program can be judged has been explored in a recent paper by Agnich and Dunlap (1959). These authors suggest that means be established for evaluating the performance of each phase of an exploration program in terms of its predicted performance.

A prominent phase of many exploration endeavors consists of carrying out seismic surveys. Large portions of the world in which exploration activity is conducted can be characterized seismically as areas of poor record quality. Areas in which usable or even good seismic data were secured in the past may be considered poor in terms of contributing information on a specific or a new objective. Further, to realize fully the potential offered by modern data processing as means for solving difficult interpretive problems, it is necessary that the seismic data be recorded initially on the magnetic media in the best possible form. The task often arises, then, of determining the cause of inadequate record quality and of making practical estimates about what it takes to achieve a solution. This information is necessary in order to set up certain standards of performance for a particular situation.

A frequently used approach to the solution of a record quality problem, which was often adequate in the past, was the trial and error method. The chief disadvantages of this approach are four-fold. First, the rate of convergence toward a

* Manuscript received by the Editor October 5, 1959.

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solution may be too slow. Second, recording techniques developed may be more elaborate and hence more costly than a simpler one which may be satisfactory. Third, if the problem to be solved is particularly difficult, a usable solution may be missed altogether. Fourth, the results of such procedures yield little information on how to modify techniques to meet changing conditions over the prospect.

An alternate approach consists of carefully controlled experimental tests designed to place in evidence essential features of the signal and noise characteristics. From a knowledge of these characteristics, it is possible to formulate the nature of the problem and, by combining this knowledge with the known behavior of the various recording methods, to estimate possible solutions. The methods or tools which the geophysicist may control to achieve an improvement in signal-to-noise ratio are the type of seismometer, method of planting, the number of seismometers in a group, the number of simultaneous shots, configuration of shot and seismometer arrays, shotpoint offset, charge size, shape of charge, charge depth, and filter-pass bands. The uses and functions of several of these recording parameters have been given careful theoretical treatment in the published literature. The wide range of capabilities of modern seismic instruments and instrument requirements for operations in difficult record areas have been discussed by Hammond and Hawkins (1958).

The theory and design of multiple seismometer arrays have been treated according to different points of emphasis by many authors, a partial listing of which would include Lombardi (1955), Parr and Mayne (1955), Smith (1956), Savit, Brustad, and Sider (1958), and White (1958). The conclusions of these authors about the applicability of multiple seismometer techniques vary somewhat according to the initial assumptions made about the problem, particularly about the noise characteristics. A noise analysis procedure designed to secure estimates of the properties of the reflected signals and the interfering noise as a basis for designing an optimum recording technique is described by Smith (1956).

Although theory has been treated in the literature, its application has not been fully exploited in practice. The need for its routine use in poor record areas is pointed up by the observations of Hammond and Hawkins (1958). These authors suggest that when a normal seismic record is obtained completely devoid of identifiable reflections, it is not possible to determine whether the signal-to-noise ratio is one to three or one to one hundred. In the first instance satisfactory records could probably be secured by several different combinations of recording devices. Here the concern would be the one of determining the most efficient and hence the most economical technique from several possible ones. For a situation in which the signal-to-noise ratio is in the vicinity of one to one hundred, it may or may not be possible to secure usable data by any known techniques. Obviously, in planning a seismic survey in a poor record area, it becomes vitally important to find where, in such a wide range of possible ratios of signal and noise, the actual signal lies.

The interfering noise can be defined in many ways. In seismic work, it is con-

venient to define the signal as any information-bearing wave or component of a wave which we desire to isolate. This information constitutes the data employed to develop the ultimate geologic interpretation. The noise then consists of all the remaining disturbances which appear on the records. Defined in this manner, the noise consists of (one) complex disturbances which are random in both amplitude and phase, and (two) coherent waves having identifiable characteristics. The coherent or systematic noise waves are commonly surface or near-surface waves initiated by the shot impulse. Under special circumstances, they may be multiple reflections, reflected refractions, refractions from shallow interfaces, or diffractions from sharp localized features. Results from careful studies of investigations into properties of shot-generated surface and near-surface waves have been reported by Howell, Neuenschwander, and Pierson III (1953) as well as by Dobrin, Lawrence, and Sengbush (1954). The results reported in the latter paper disclose a remarkable variety of coherent boundary waves. It is clear that the possible range in properties of noise is extremely broad but that in a specific situation, these properties may be bounded within narrow limits.

In Figure 1 are shown four pattern arrangements and their theoretical response curves to plane waves traveling in the direction of the seismic profile. The range of wave length distributions for two assumed noise conditions, both of which have been observed in actual tests, are shown. The noise locations refer to the dominant interfering noise occurring at ranges of record times at which it is desired to obtain usable reflection data. The illustration suggests two results, both of which have been observed in practice. One is that the behavior of the response curve can be critical. This is the situation for Noise I. Here the sharper cutoff needed to reject the noise wave lengths lying immediately adjacent to the signal is provided by the pattern most easily constructed, the linear array. The second result is that the response of several kinds of patterns, for example, patterns A and C may be nearly equivalent. Although the construction of one pattern is much more complicated than the other, each should yield a comparable improvement in record quality for the assumed conditions of signal and noise. A pattern of type B should be somewhat better than A and C if only Noise II exists. Pattern D is not optimum for any of the postulated noise conditions. This example suggests that knowledge of the problem is required to guide the proper selection of any array.

If complete knowledge of the signal and noise characteristics of an area were available, it would be possible to specify uniquely a best recording technique. Accepting the fact that field experimental work must be limited, one real task of practical geophysics, then, is the devising of simple tests to reveal the nature of specific problems and to adapt this knowledge to the design of recording techniques adequate to meet changing conditions around the prospect. Such tests must be simple enough to be performed reasonably fast with normal instrumentation and must yield data which can be interpreted by the normal staff concurrent with the shooting.

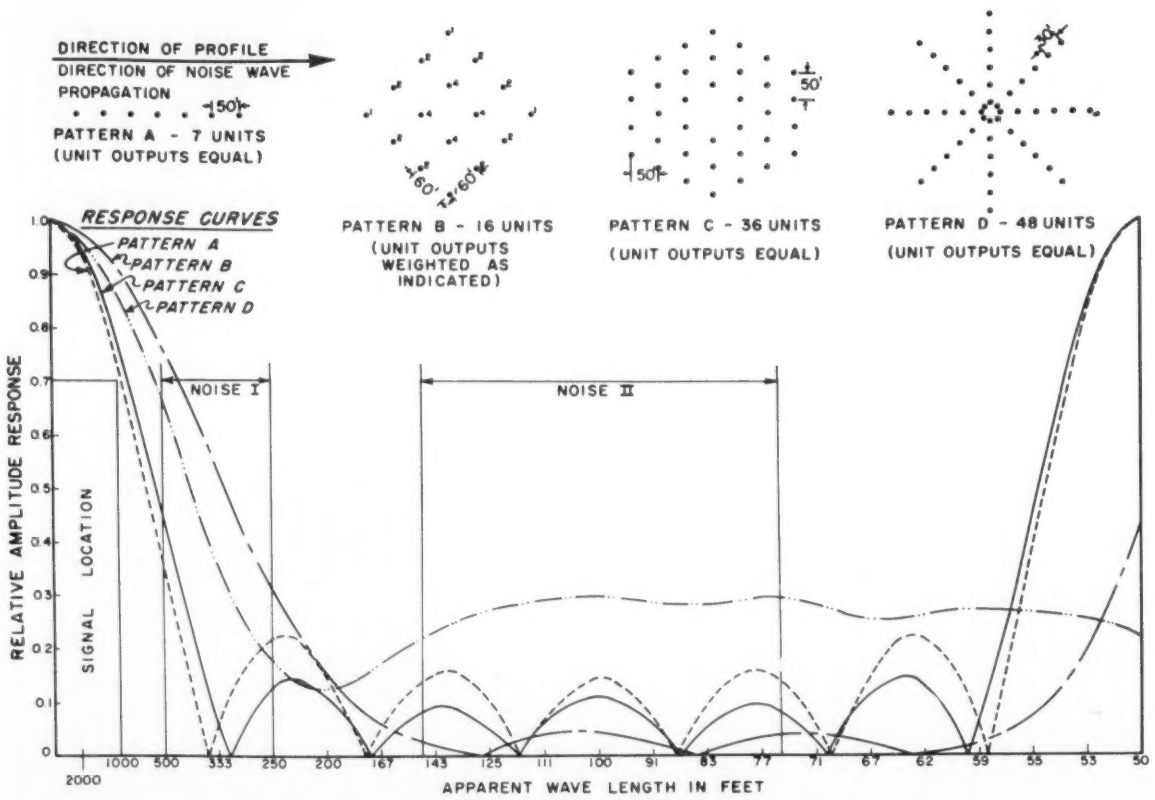

FIG. 1. Theoretical wave length response functions for plane waves traveling along direction of profile for four pattern arrangements. Applicability of array depends upon assumed noise condition.

The purpose of this paper is to describe one company's experience in investigating record quality problems in a routine fashion with an analytical type of testing procedure. This description is carried out by presenting one example in a case history form.

NATURE OF EXPERIMENTAL PROCEDURE

The testing process consists of the following four general phases: (one) the collection of data providing measures of chiefly those signal and noise characteristics useful in considering design of an optimum recording technique, (two) the interpretation of these data to identify the troubles which limit seismic record quality, (three) the prediction of solutions, and (four) the carrying out of simple tests to evaluate how well the problem responds to the predicted solutions.

A complete noise analysis is generally out of the question. The practicing geophysicist is confronted with the problem, on the one hand, of conducting an experiment with all factors held constant except the one whose effectiveness he wishes to isolate and, on the other hand, of attaining a satisfactory solution to a field problem with a practical amount of time and money. The conditions of the experiment often affect to some degree the evaluation of the parameter under investigation. It is apparent that a compromise must be struck between the detail of the data which can be obtained experimentally and operational considerations.

The wave form tests and interpretive procedures to be described represent a compromise which has been found to be a practical way of reducing theory to practice. The emphasis is on combining knowledge of the theoretical properties of recording devices with knowledge of the existing signal and noise conditions as revealed by experimental sampling to achieve useful data in an economical manner. The testing procedure follows the form outlined by Smith (1956).

CASE HISTORY

Test Site

The prospect is in an area where the oil operator had conducted earlier seismic surveys. Identification of this prospect and detailed structural information is omitted in this discussion at the request of the company owning the data.

A test site was selected in a part of the prospect in which the records were poor but not completely without evidence of reflected signals. The plan was to make the tests where measures of both the signal and noise could be secured and then to proceed into the "no reflection area" by performing abbreviated tests to determine whether the noise intensity or the signal level was changing. Through such observations, the operators sought to infer whether the change in record quality was attributable to variations in noise intensity or to the alteration of the signal owing to changing subsurface structural relationships.

A sample of the seismic data recorded in an earlier survey in the vicinity of the test site is shown in Figure 2. Although these data may have been useful in aiding the original exploration effort, seismic data of considerably improved quality were required to be consistent with the new exploration objectives. A

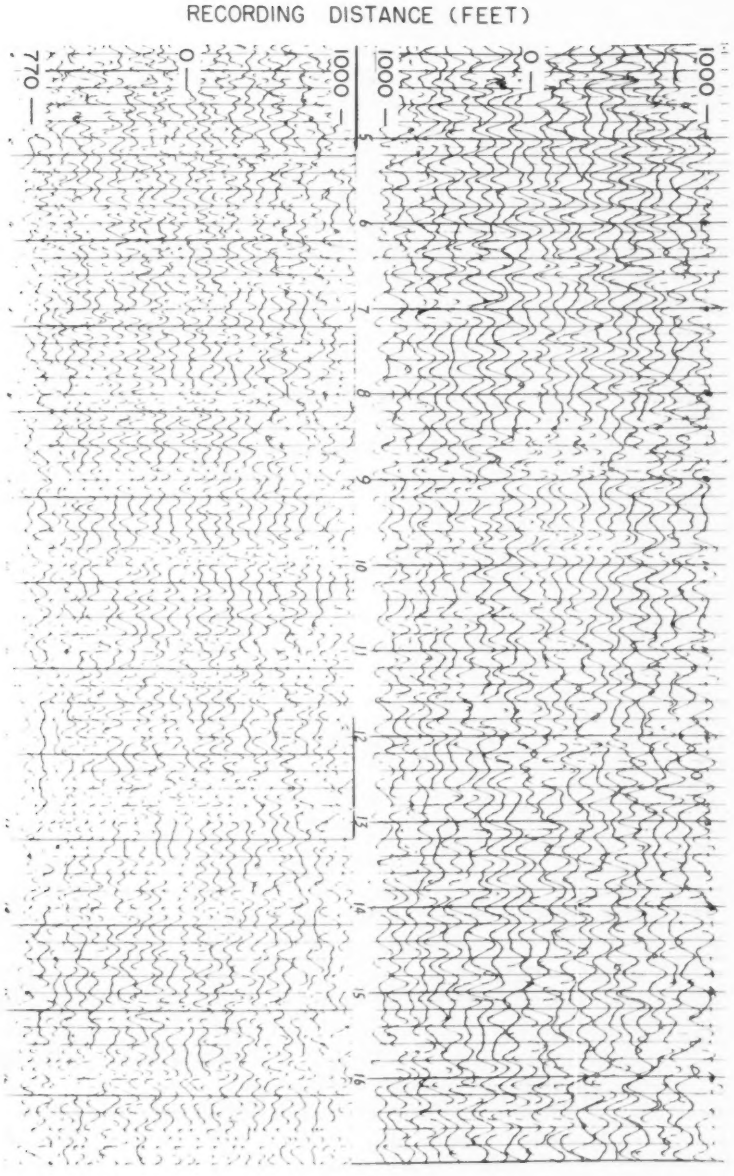

FIG. 2. Sample of quality of data secured in a prior seismic survey of prospect. Seismograms were recorded with one shothole, 2½ pound charges, and six seismometers per group.

study of these records does not reveal the specific causes of the poor record quality. It was the purpose of the tests to determine whether records adequate for the new exploration objectives could be obtained, and if so, to reveal the most efficient recording techniques. This program consisted of a sequence of tests designed to examine the effect of each variable on record quality insofar as seemed necessary. The test results shown in this paper, by way of illustration and discussion, are presented as typical samples characteristic of each test.

Test of Signal and Noise Characteristics

The basic data were recorded on a consecutive sequence of spreads ranging from 200 to 1,600 ft from a single shotpoint location. Charge sizes and hole depths were those thought to be typical for the area. The recording spreads consisted of single seismometers spaced at ten-ft intervals. Damped seismometers having a natural frequency of 14 cps were used for the most part; but on occasion, to investigate the filtering action of seismometers with respect to the observed signal and noise, both four-cycle and 27-cycle seismometers were also used.

The 14- and 27-cycle seismometers were S-32 models manufactured by Electro-Technical Laboratories, and the four-cycle seismometers were manufactured by Hall-Sears.

The recording equipment, manufactured by Texas Instruments Incorporated, consisted of a magneDISC recording unit and a 24-channel 7,000 amplifier system capable of being operated with either automatic gain control or constant gain. The frequency response of the instrumental system was flat within three decibels between 12 and 120 cps.

One constant gain recording was made at each spread setup. Replays made with automatic gain control facilitated the identification of the individual signal and noise events. The constant gain recordings allowed measurements of wave amplitudes. A sample of the data recorded in this test is shown in Figure 3. The data collected in this test were plotted on a time-distance graph shown in Figure 4, which displays the coherent events and their measurable characteristics.

The time-distance graph shows dominant sets of surface or near-surface waves between 0.6 and 2.0 seconds. Both the amplitude and frequency of these noise waves appear to decrease with increasing time and distance. A comparison of in-line and cross-spread data indicates that the strong surface or near-surface wave trains are developed by the shot and propagate outward from the shot. The dominant interfering noise appears to have a wave length distribution which peaks in the neighborhood of 45 ft. These waves have a definable set of properties extending over a limited range of values. They destroy substantially the continuity of the weaker reflected energy having arrival times up to two sec. Because of the dominance of the noise waves accurate signal measurements are difficult to make from data recorded with single seismometers. However, the most reliable measurements show that the signal-to-noise ratio varies roughly over a range from 1/1 to 1/4.

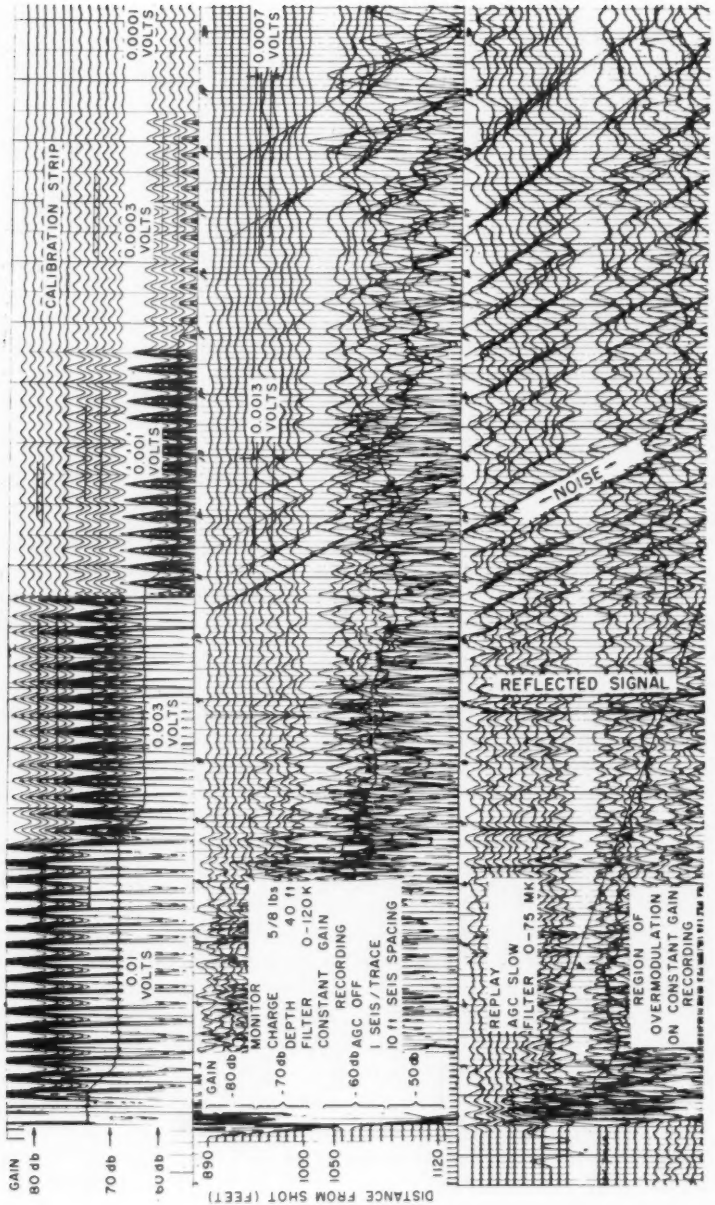

FIG. 3. A sample of the data recorded in the wave form tests. At the top is a signal calibration record. Next is shown a constant gain recording. The bottom record is a replay using automatic gain control.

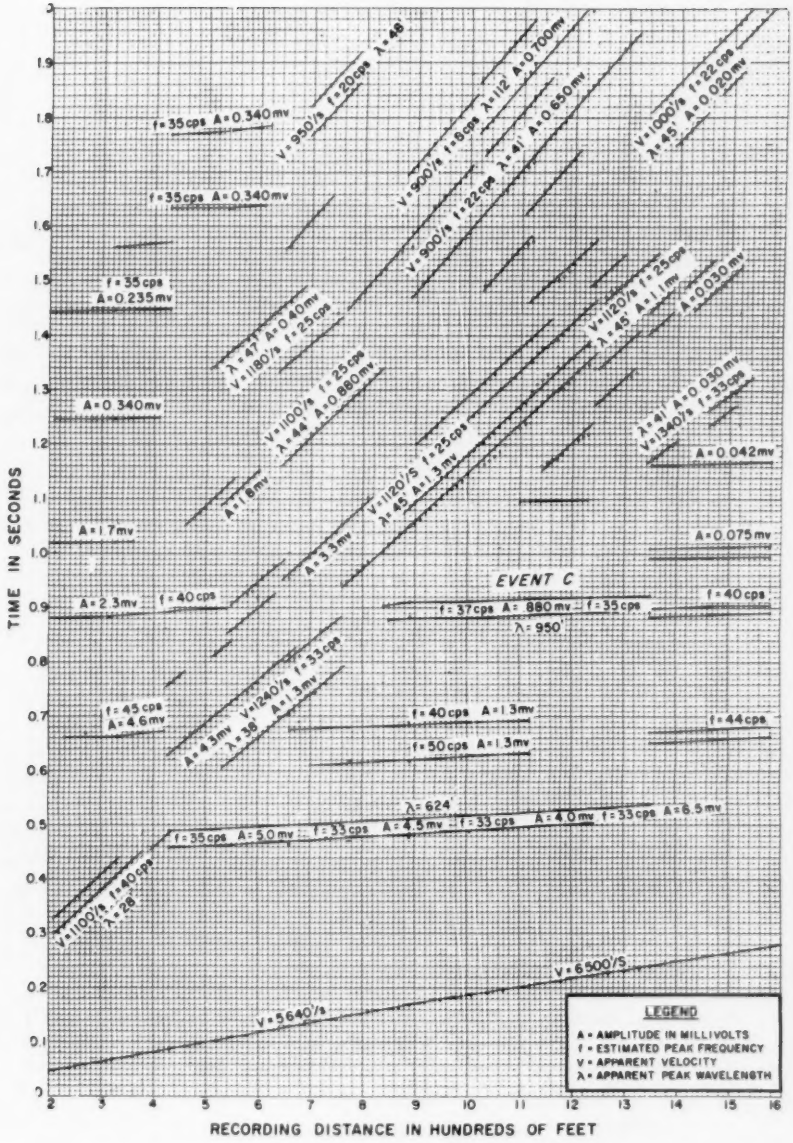
TIME IN SECONDS
RECORDING DISTANCE IN HUNDREDS OF FEET
EVENT C
f = 35cps A = 0.340mv
V = 950'/s f = 20cps λ = 48'
V = 900'/s f = 6cps λ = 112' A = 0.700mv
V = 900'/s f = 22cps λ = 41' A = 0.650mv
V = 1000'/s f = 22cps λ = 45' A = 0.020mv
f = 35cps A = 0.340mv
f = 35cps A = 0.235mv
λ = 47' A = 0.040mv V = 1180'/s f = 25cps
A = 0.340mv
V = 1100'/s f = 25cps λ = 44' A = 0.880mv
V = 1120'/s f = 25cps λ = 45' A = 1.1mv
λ = 45' A = 0.030mv
λ = 41' A = 0.030mv V = 1340'/s f = 33cps
A = 0.042mv
A = 1.8mv
A = 1.7mv
A = 3.3mv
A = 0.075mv
A = 2.3mv f = 40cps
f = 37cps A = 880mv f = 35cps
λ = 950'
f = 40cps
f = 45cps A = 4.6mv
V = 1240'/s f = 33cps
A = 4.3mv λ = 38' A = 1.3mv
f = 40cps A = 1.3mv
f = 50cps A = 1.3mv
f = 44cps
λ = 624'
f = 35cps A = 5.0mv f = 33cps A = 4.5mv f = 33cps A = 4.0mv f = 33cps A = 6.5mv
V = 1100'/s f = 40cps λ = 28'
V = 6500'/s
V = 5640'/s
LEGEND
A = AMPLITUDE IN MILLIVOLTS
f = ESTIMATED PEAK FREQUENCY
V = APPARENT VELOCITY
λ = APPARENT PEAK WAVELENGTH

FIG. 4. Time-distance graph displaying the events recorded in the tests and their measurable characteristics.

Noise which did not exhibit coherence with the 10-ft sampling interval was judged to be random. These experiments showed that the random noise was much weaker than both the reflected signals and the coherent noise waves. Hence, it was not an important consideration in designing the recording geometry.

Effectiveness of Multiple Seismometer Arrays

The test results suggested the use of multiple shot and seismometer arrays designed to reject the interfering noise by wave length discrimination.

Basis of Array Design.—Although the properties of multiple seismometer patterns are well known, there is some speculation and difference of opinion about the application of this knowledge (Savit, Brustad, and Sider, 1958). Seismometer arrays can be treated as filtering devices whose response characteristics are a function of apparent horizontal wave lengths rather than frequencies. For example, the theoretical wave length response of a linear pattern consisting of six seismometers spaced uniformly at 15-foot intervals in line with the shot is shown in Figure 5. Since both the signal and noise waves are transient pulses, both are represented by broad frequency and wave length distributions rather than by single values. Commonly, the wave length distribution of the noise spans several of the zero and maximum points of such a theoretical seismometer curve. Hence, to predict the attenuation of a given noise relative to the signal achieved by any particular array, an average curve is more useful than the theoretical one. The

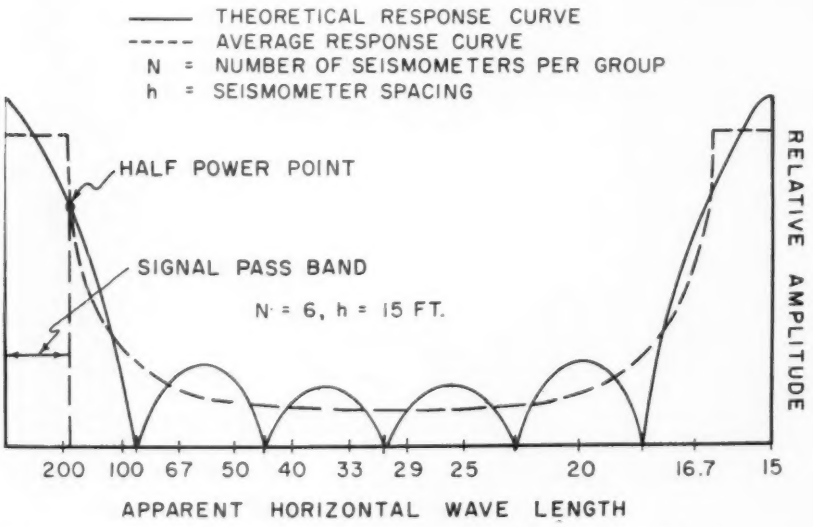
THEORETICAL RESPONSE CURVE
AVERAGE RESPONSE CURVE
N = NUMBER OF SEISMOMETERS PER GROUP
h = SEISMOMETER SPACING
HALF POWER POINT
SIGNAL PASS BAND
N = 6, h = 15 FT.
RELATIVE AMPLITUDE
200 100 67 50 40 33 29 25 20 16.7 15
APPARENT HORIZONTAL WAVE LENGTH

FIG. 5. Comparison of a theoretical and an average wave length response for a line of six seismometers spaced uniformly at 15-foot intervals.

method of averaging depends upon the definition of the band-pass and band-reject regions. The criterion for selection of a filter-pass band is based on the capacity of the filter to pass the signal within specified limits of distortion while rejecting the greatest amount of noise. The band-pass region of the multiple seismometer array was defined to be that portion of the region between the point of maximum response and the wave length for which the response is down 50 percent in power. This choice of cutoff point corresponds to that of the conventional high-cut filter thought to be optimum for the reflection. To obtain the average response curve shown in Figure 5, the theoretical response curve was averaged at uniform intervals. These average amplitudes were then normalized with respect to the average amplitude in the band-pass region. This method of defining the band-pass and reject regions and of constructing averaged response curves is consistent with the criteria used for selection of electrical filters and is applicable to any type of array.

The maximum group length is limited by the requirement that the shortest signal wave length necessary to preserve reflection character falls within the signal pass band. The wave length response curves considered are periodic. For this reason the maximum seismometer spacing is governed by the shortest noise wave length passed through the electrical filter pass band. If we restrict the choice of arrays to a line of uniformly spaced seismometers having equal outputs, the above considerations set the following two criteria for selecting N, the total number of units in an array, and h, the seismometer spacing (Smith, 1956).

(1) Maximum group length is such that the product

$$Nh = 0.45\lambda_s, \quad \text{where} \quad \lambda_s = \frac{V_{s\,\min}}{f_H}.$$

In these equations, $V_{s\,\min}$ is the smallest value of the apparent horizontal velocity of the reflected signal, f_H is the highest frequency necessary to preserve reflection character, and λ_s is the corresponding shortest signal wave length. This f_H should coincide with the highcut filter setting. Values of $V_{s\,\min}$ can be estimated from considerations of section velocity, depth to reflecting interface, recording distance, and dip. Use of this criterion assures that wave lengths of the reflected signals equal to or greater than λ_s will fall in the region between the maximum response and the half-power point.

(2) The limitation on the maximum seismometer spacing is given by

$$h_{\max} < \frac{V_{n\,\min}}{f_H}.$$

In this expression, $V_{n\,\min}$ is the slowest noise velocity, a measure of which was obtained in the test results shown in Figure four.

Relation to Problem.—Gross estimates of the frequency distribution and the apparent wave length distribution of the signal and noise are shown in Figure 6.

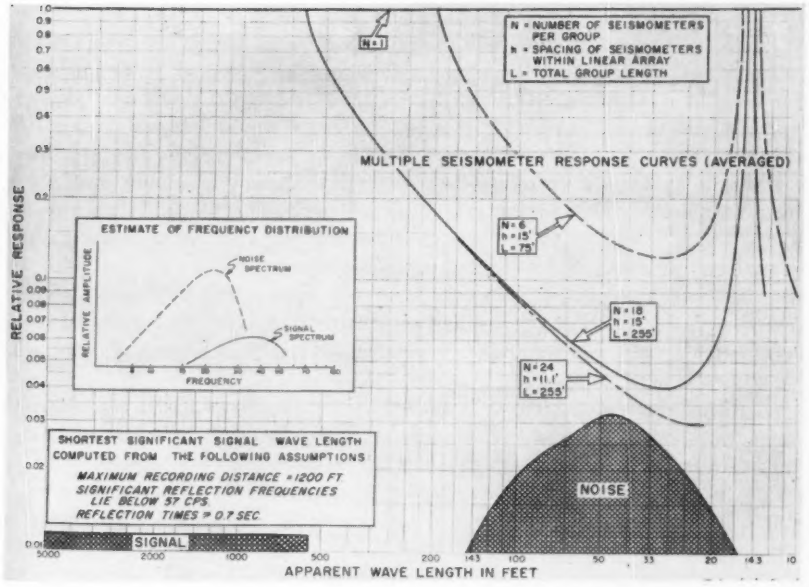
N = NUMBER OF SEISMOMETERS PER GROUP
h = SPACING OF SEISMOMETERS WITHIN LINEAR ARRAY
L = TOTAL GROUP LENGTH
MULTIPLE SEISMOMETER RESPONSE CURVES (AVERAGED)
N=1
N=6 h=15' L=75'
N=18 h=15' L=255'
N=24 h=11.1' L=255'
RELATIVE RESPONSE
ESTIMATE OF FREQUENCY DISTRIBUTION
NOISE SPECTRUM
SIGNAL SPECTRUM
RELATIVE AMPLITUDE
FREQUENCY
SHORTEST SIGNIFICANT SIGNAL WAVE LENGTH COMPUTED FROM THE FOLLOWING ASSUMPTIONS
MAXIMUM RECORDING DISTANCE = 1200 FT
SIGNIFICANT REFLECTION FREQUENCIES LIE BELOW 57 CPS
REFLECTION TIMES = 0.7 SEC
SIGNAL
NOISE
5000 2000 1000 500 200 143 100 50 33 20 14.3 10
APPARENT WAVE LENGTH IN FEET

FIG. 6. Estimated frequency and wave length distributions of the signal and noise. The average response curves for three kinds of seismometer arrays are shown.

These estimates were made over a time range of 0.7 to 2.0 secs and a recording distance range of 100 to 1,600 ft. The frequency measurements are relatively crude in that they were made visually on paper records without benefit of accurate frequency analyzing equipment. Even after making allowances for errors in the estimated spectra, the measurements show that the signal and noise partially overlap in frequency but are considerably separated in wave length. The dominant noise appears to be localized in a particular region. It is evident that a complete separation of signal and noise cannot be achieved by electrical filtering alone. On the other hand, the substantial separation in the wave length distributions of the signal and coherent noise suggests that the enhancement of the desired signals by wave length filtering devices, such as arrays of seismometers, could be very effective.

Based on estimates of the signal and noise properties and the above mentioned criteria, the optimum seismometer pattern of linear density appeared to be 18 seismometers spaced uniformly at 15-ft intervals in line with the shot. Theoretically, use of this pattern should yield roughly a signal-to-noise ratio improvement of 20 to 1 over that provided by one seismometer and a 3 to 1 improvement over that provided by a pattern of six seismometers. The average ap-

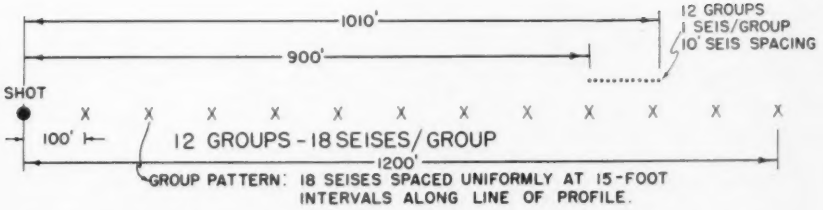

FIG. 7. Plan view of recording geometry used to record most of the experimental seismograms.

parent wave length response curves for these patterns are shown in Figure 6. The amplitude response curve for 24 seismometers per group indicates that there is essentially no additional benefit to be gained by adding six more seismometers to the pattern of 18 seismometers per group.

To test the validity of the analysis, brief experiments were conducted which allowed a quick comparison of actual results with those predicted by theory. The results of using the theoretically optimum pattern were compared with the results using arrays having appreciably different response characteristics in order to estimate the accuracy of the prediction.

The efficacy of the 18-seismometer pattern in rejecting the disturbing noise relative to a single seismometer per group was examined by using foldback spreads of the type shown in Figure 7. Recordings were taken with both fixed gain and automatic gain control. An example of a seismogram recorded by the latter method is shown as the top record in Figure 8. The spread, consisting of one seismometer per group, stretched between groups nine and ten of the multiple seismometer spread. Since no electrical filtering was done in the frequency range of interest and since a common shot was used, a comparison of the data from the two spreads should give a measure of the wave length filtering property of the pattern array. The diagonal line across the record notes the position at which the near-surface waves first hit each group. Before the noise waves arrive, reflections can be observed almost as well with single seismometers as with multiple seismometers. However, the noise waves almost completely obliterate all evidence of reflected events "D," "H," and "E" on the single seismometer traces whereas these reflections are well developed on the traces recorded with the pattern array. From previous considerations, one would expect such an improvement in appearance.

A comparison of the relative effectiveness of two different seismometer patterns is shown as the bottom record in Figure 8. In each instance the seismometers were spaced uniformly at 15-foot intervals in line with the shot. The data were recorded from a single shot on a foldback spread of the type illustrated beneath the seismogram. Again, before the noise waves arrive, reflections of the same quality were observed on each spread. In the region disturbed by the noise,

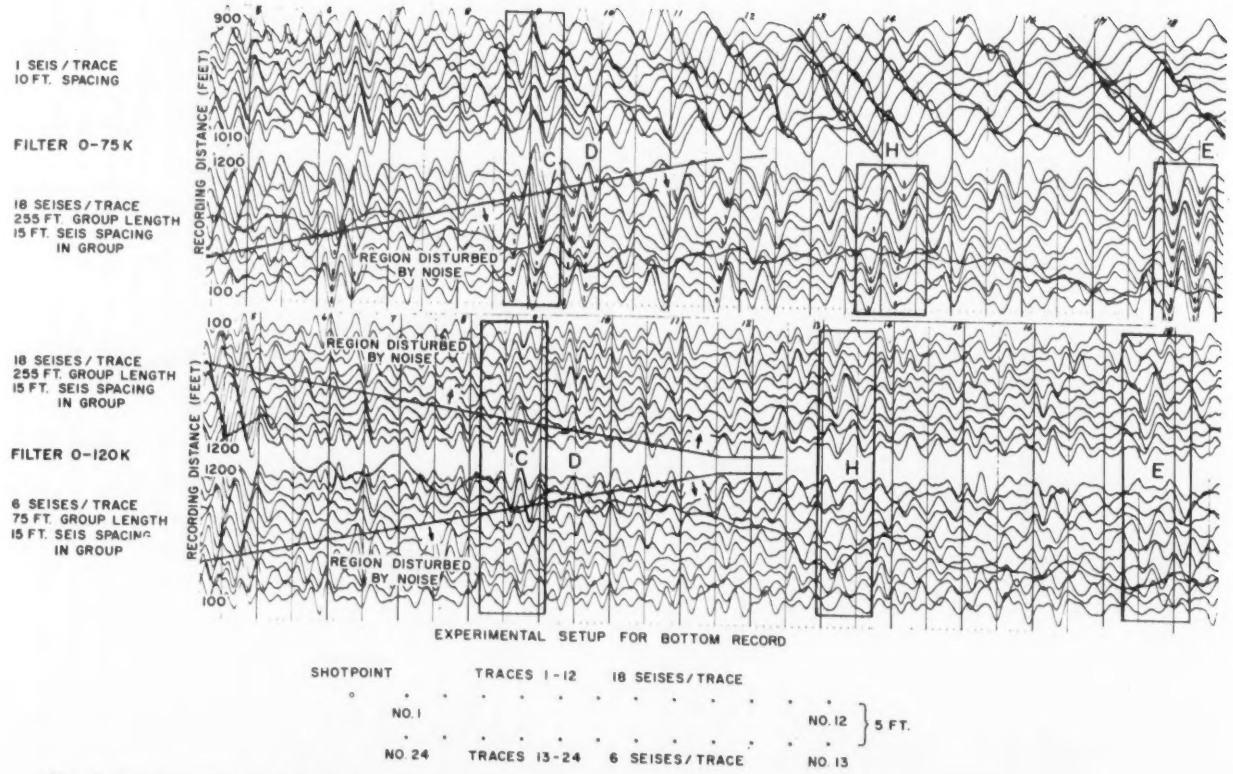

FIG. 8. Two comparisons of the effectiveness of multiple seismometer patterns. Experimental recording arrangement for top seismogram is shown in Figure 7. Seismometers in patterns are placed in a line along direction of profile at uniform intervals.

however, a significant improvement in record quality is provided by the pattern of 18 seismometers. The array of six seismometers per group was compared with the theoretically optimum linear array to establish whether the expected improvement in signal-to-noise ratio was observable.

The fact that these foldback tests provided results approximately as predicted, suggested that the use of multiple seismometers could be applied objectively over the prospect according to simple theory and that needed modifications in the array could be made in accordance with knowledge of changing conditions. The test suggested that the usefulness to be gained in compositing outputs could be predicted in a similar fashion.

Variations in elevations and weathering thickness decrease the effectiveness of the array by attenuating the higher frequencies in the signal spectrum. How large a variation in these variables can be accommodated in a particular situation can be estimated by calculating the changes produced in $V_{s\,\min}$ and hence in λ_s. The lack of marked deviations of observation points from the time-distance curve of the first refraction arrivals shown in Figure 4 suggested that erratic time delays would not present a significant problem.

Effect of Hole Depth on Signal-to-Noise Ratio

In addition to conventional uphole velocity surveys, shots were recorded at several depths with constant gain amplifiers making use of an experimental arrangement similar to that shown in Figure 7. A sample of the test seismograms and a plot of the signal-to-noise ratio as a function of hole depth is shown in Figure 9. In this case, the spread of single seismometers recorded the input signals arriving at the eleventh and twelfth multiple seismometer groups. The particular type of spread geometry was chosen in order to secure a measure of both the desired reflected signal and noise from the same shot. Because of the dominant noise recorded with the single seismometers, amplitudes of the reflected signals were measured from the data recorded with patterns of seismometers. Noise amplitude measurements were made on seismograms recorded with single seismometers. For this reason, the signal-to-noise ratios indicated on the graph in Figure 9 represent the true ratio multiplied by a constant factor characteristic of the recording geometry.

Two marked changes in the properties of the reflected events occurred with respect to hole depth. These are the decrease in amplitude and the increase in frequency with increasing charge depth. In general the amplitude and frequency changes in the disturbing noise waves are considerably less than are those in the reflected events. Note that the noise amplitudes of the 100-ft shot are nearly the same as those of the 40-ft shot. The tests indicated that superior results were secured with 40-ft shots.

The reason for the rapid decrease in reflection amplitude and increase in frequency was not clearly understood. The drill logs showed very little change in the near-surface materials with hole depth. Part, but not all, of the progressive change

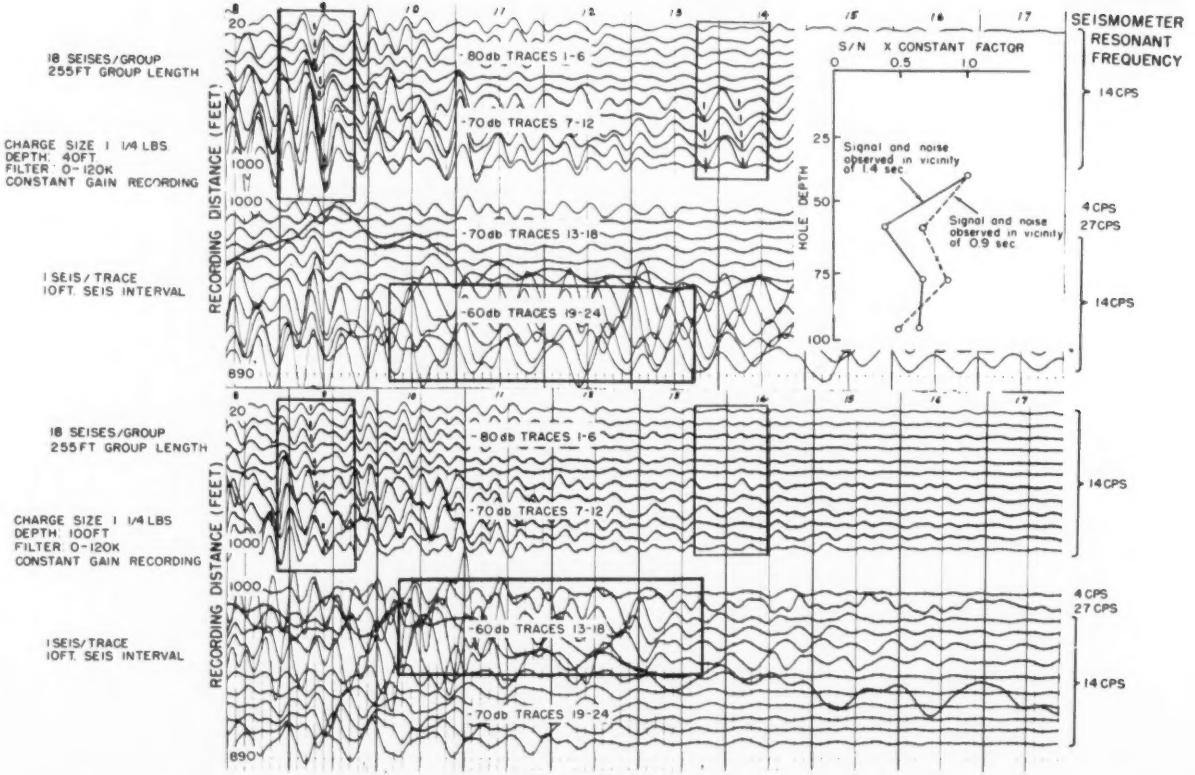

FIG. 9. Sample constant gain seismograms from charge depth test. Reflection character changes rapidly but noise remains nearly constant. For plot of signal-to-noise ratio vs hole depth, noise is measured on spread of single seismometers and signal on spread of pattern seismometers.

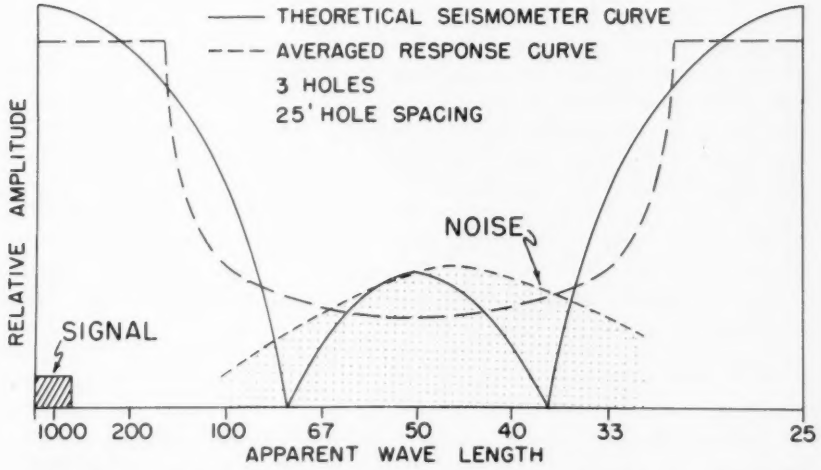

FIG. 10. Theoretical and average response curves of a pattern of three holes spaced at 25-foot intervals. Interfering noise falls in the general reject region. Tests of this shot pattern are shown in Figure 11.

in character with hole depth was attributable to the ghosting effect (Van Melle and Weatherburn, 1953, Musgrave, Ehlert, and Nash, 1958). It is possible that the shotpoint environment may change in such a manner that the pulse propagating outward from the deep shots may contain a much higher proportion of high frequencies than the pulse from shallow shots.

Because of the dependence of the design of pattern shots or seismometers on the properties of the noise, knowledge of whether the reflected signals or the type of interfering noise changes with hole depth becomes important in design considerations. For this reason the uphole tests were conducted as described. Such information would be partially obscured by conducting these tests with conventional reflection profiles recorded with automatic gain control.

Effectiveness of Multiple Holes

The fact that the multiple seismometers behaved approximately as postulated suggested the use of multiple holes as an additional wave length filter. A record shot with a three-hole pattern was compared with one shot with a single hole making use of the type of experimental setup shown in Figure 7. The three holes were spaced 25 ft apart along the profile line. The shot spacing was selected so that the dominant noise fell in the middle of the reject region of the wave length response curves of the shot pattern as shown in Figure 10. The total charge sizes for the two records were maintained essentially constant. Examples of both automatic gain control and constant gain recordings are shown in Figures

11 and 12. Note on the constant gain recording that the continuity of the noise waves observed with a single shot at the −80-db setting is considerably broken up by the three-hole pattern. Comparing the ratio of the signal-to-noise ratios measured from individual records, over the time range from 0.7 to 2.0 sec, reveals that the use of the three-hole pattern improves the signal-to-noise ratio three to four times. This improvement is approximately what one would predict. It suggested that should the signal-to-noise ratio become significantly worse, larger patterns of holes could be employed to advantage and that the advantage to be gained could be predicted according to design criteria similar to those employed for pattern seismometers. Alternatively, perhaps vertically distributed charges having equivalent wave length response characteristics could be employed (Musgrave, Ehlert, and Nash, 1958).

Study of Charge Size

The sizes of the explosive charges suitable for the prospect were characteristically small, and charges larger than two pounds were prohibited by permit restrictions over much of the prospect. Studies of the effect of charge size on the signal-to-noise ratio were conducted utilizing again the type of experimental setup illustrated in Figure 7. A sample of the test results is shown in Figure 13. In this example, the size of the charge used to record the top profile was approximately three times that for the bottom one. The recordings were made with constant gain and a 0–120 cps K-type filter pass band. Note that the noise waves between 1.0 and 1.3 secs at the −70db gain setting are essentially the same on both profiles, whereas the amplitudes of reflected events C, D, H, and E changed significantly. To remove the shot coupling variable insofar as possible, the ratio of the signal-to-noise ratios on one profile to the ratios on the other for corresponding events was determined. This calculation showed tripling the charge size increased the signal-to-noise ratio by a factor which varied between 1.5 and 2, over the time range between 0.7 and 2.0 sec. Even the smallest charge of $\frac{5}{8}$ pounds produced energy levels many times greater than the preshot background noise level. No reason was determined for the apparent non-linear behavior of surface waves and compressional waves with variation in charge size. The observation was taken as a characteristic of the signal and noise behavior, and this behavior was utilized to guide the design of the recording technique.

Effectiveness of Frequency Filtering

Attenuation of noise by frequency discrimination can be accomplished by electrical filtering or by choice of the resonant frequency of the seismometers.

Repeated playbacks of test records through the magneDISC were made to evaluate the effectiveness of various low-cut filters in rejecting noise waves while preserving the reflection character. In Figure 14 are displayed a suite of records in which all the recording parameters are constant except the low-cut filter setting. The four bottom profiles are constant gain replays of the top profile. The record-

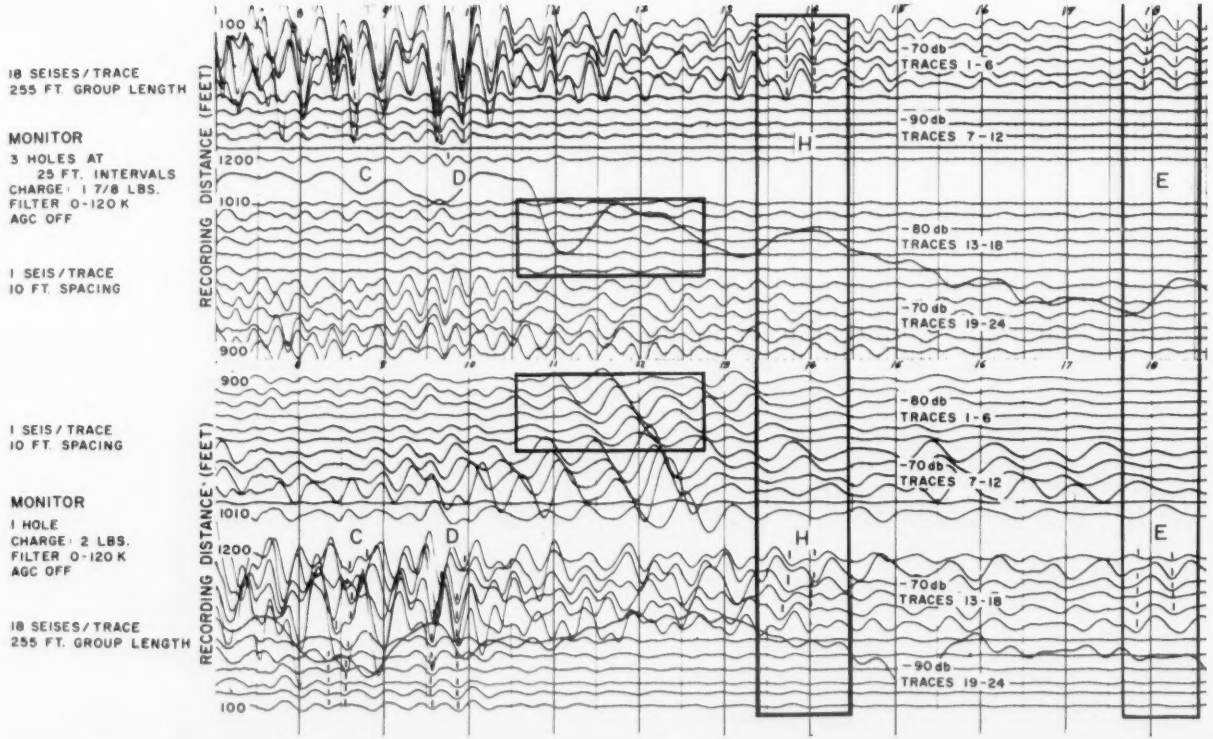

FIG. 11. Constant gain recordings to test effectiveness of multiple holes. The three-hole pattern yields an increase in signal-to-noise ratio three to four times that yielded by a single shot. Recording geometry is shown in Figure 7.

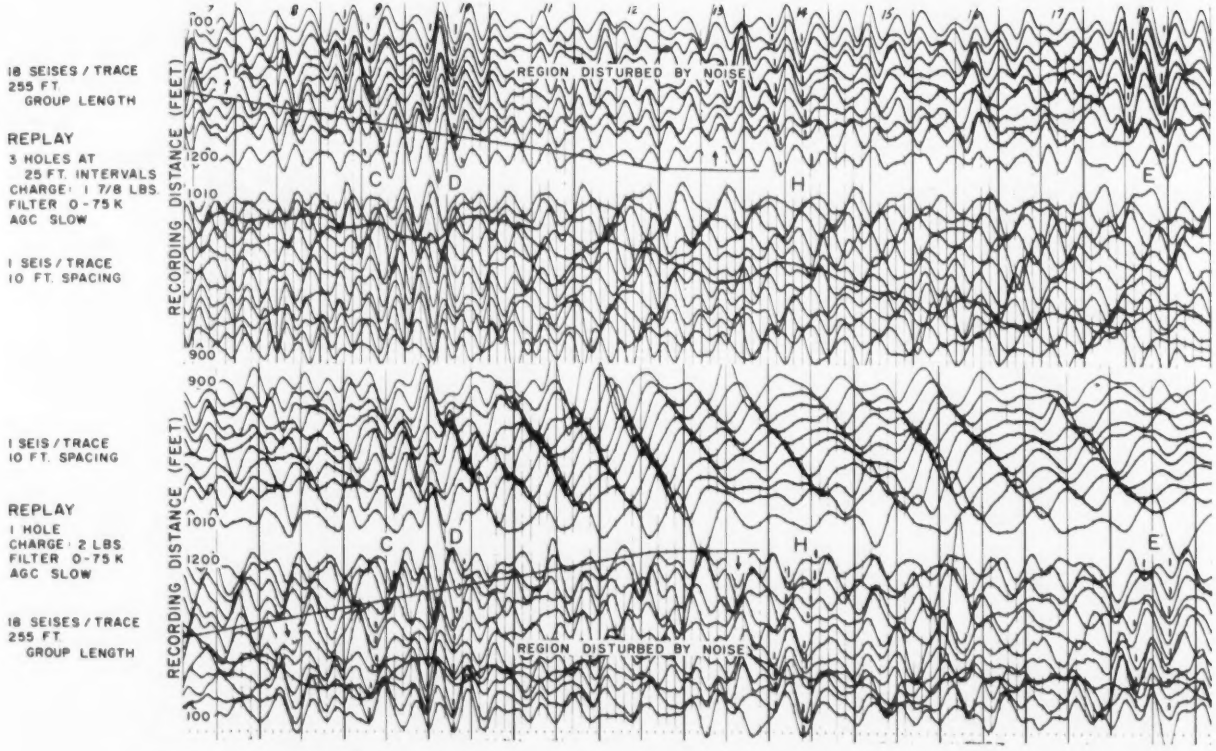

FIG. 12. Replays of seismograms shown in Figure 11 made with automatic gain control. Improvement in general record quality provided by the three-hole pattern is evident on these seismograms displayed in more conventional form.

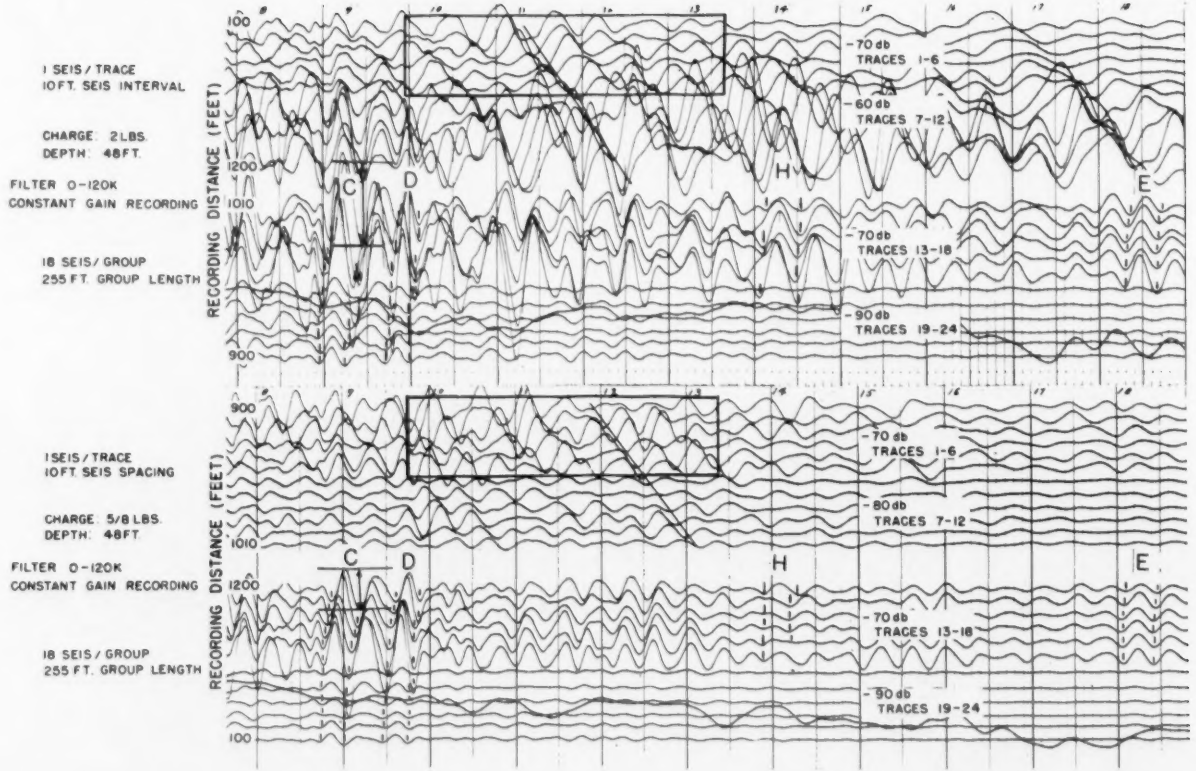

FIG. 13. Sample seismograms secured in study of effectiveness of charge size. Both charges are sufficiently large to yield energy levels greater than the preshot level. The larger charge yields an improved signal-to-coherent noise ratio. Recording geometry is shown in Figure 7.

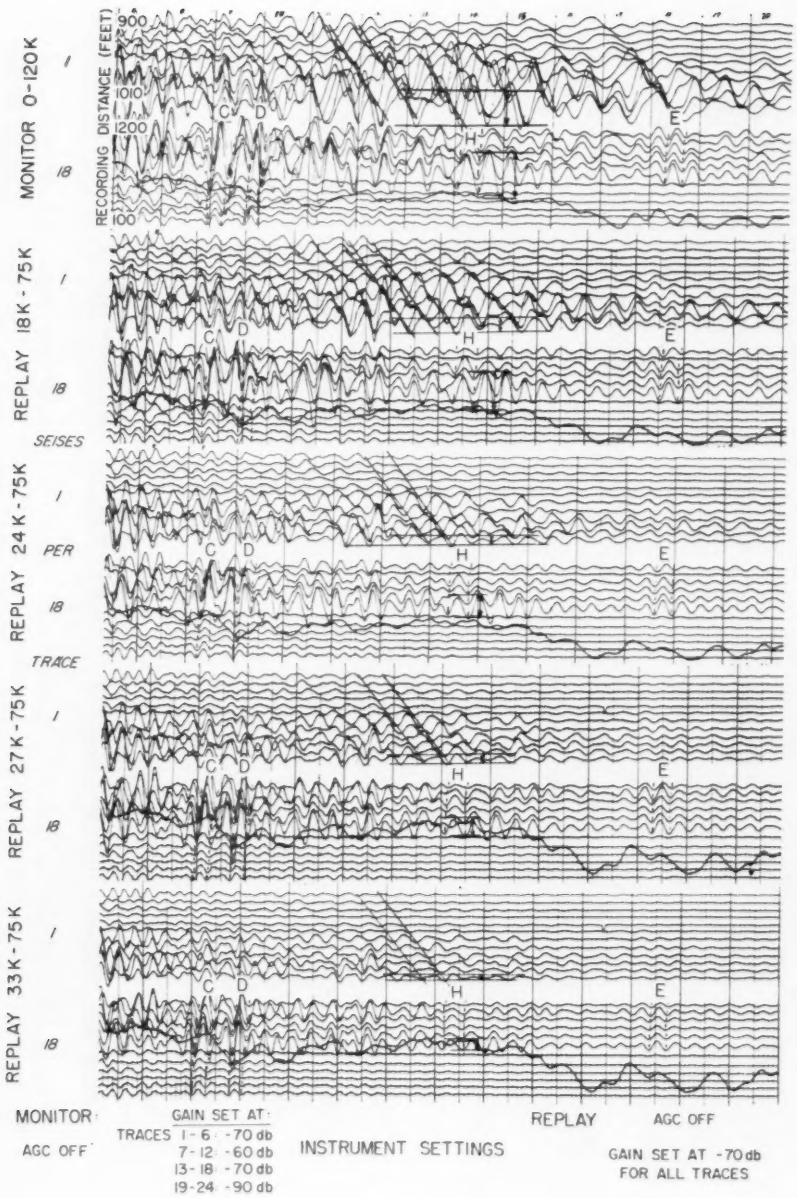

FIG. 14. Study of signal-to-noise ratio with respect to low-cut filter setting. Bottom four records are constant gain replays of top record. Recording geometry is shown in Figure 7.

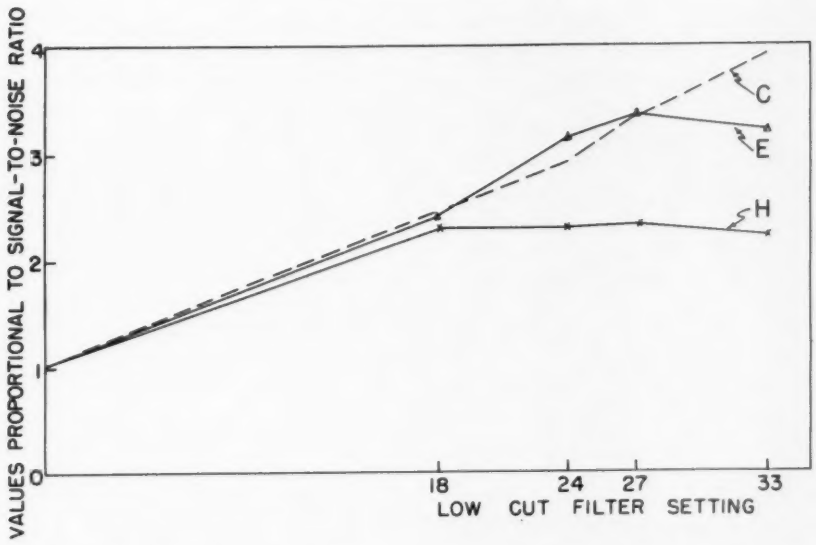

FIG. 15 Plot of signal-to-noise ratio as a function of low-cut filter setting for three reflections. Signal-to-noise ratio of event "H" does not improve by increasing the low-cut filter setting beyond 18 cps.

ing geometry used to obtain this profile was similar to the one shown in Figure 7. Signal-to-noise ratio measurements were made for several events on each record by measuring the noise on the traces representing single seismometers and the reflected signals on the traces representing multiple seismometers. Figure 15 shows the measured signal-to-noise ratio as a function of the low-cut filter for three events. The ratio values have been normalized with respect to the value existing on the open filter shot. This graph shows that a significant improvement is achieved by increasing the value of the low-cut filter to 18 cps on all events but that no additional relative rejection of low frequencies occurs for some events with additional filtering. This behavior suggests that, with low-cut filters higher than 18 cps, the signal is being filtered approximately as rapidly as the noise, with an attendant loss of reflection character. For this reason, a low-cut filter in the vicinity of 15 to 20 cps appeared to be an optimum choice.

Shown in Figure 16 is a filtered replay of the bottom record displayed in Figure 8. Note that in the region disturbed by the noise, the improvement provided by the pattern of 18 seismometers is approximately the same on the filtered record as on the unfiltered one shown in Figure 8. This particular test provides additional evidence of the overlapping of the signal and noise spectra and demonstrates that one cannot expect to achieve a solution to the record quality problem through electrical filtering alone.

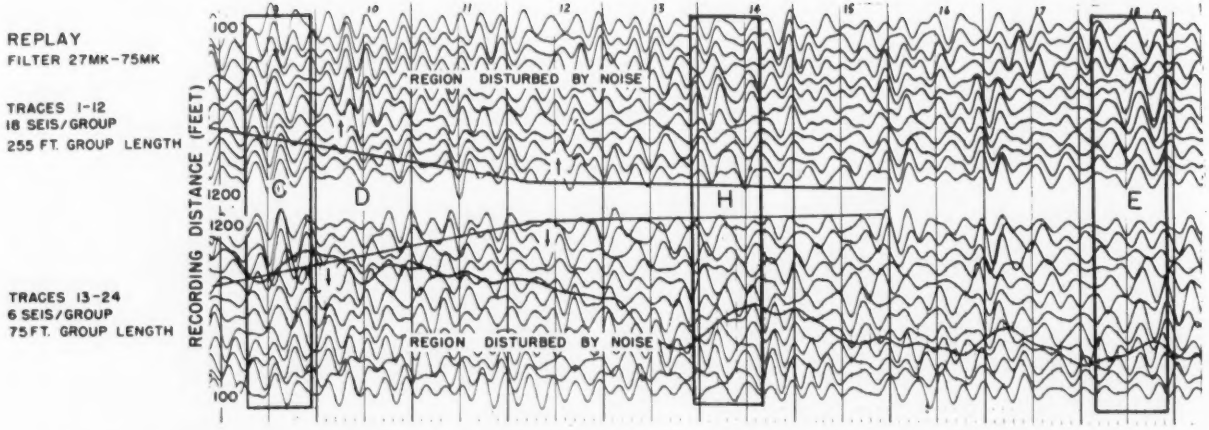

FIG. 16. Replay of bottom seismogram shown in Figure 8 with a 27 MK low-cut filter. Approximately the same degree of improvement is provided by the pattern of 18 seismometers on the filtered seismogram as on the unfiltered one shown in Figure 8.

Recordings were made at various stages in the experimental tests in which the filtering properties of 27-cycle, 14-cycle and 4-cycle seismometers were examined. One such comparison is shown in Figure 9. Although not demonstrated in Figure 9, the preponderance of evidence from tests of this nature showed that an improvement in signal-to-noise ratio could be achieved by substituting the 27-cycle seismometers for the 14-cycle type, but that this improvement was secured with some sacrifice in reflection character. For this reason, and because it was possible to attenuate severely the disturbing noise by wave length filtering, the 14-cycle seismometers were employed.

Utilization of the 14-cycle seismometers arrayed in patterns and a small amount of low-cut filtering permitted the use of the full dynamic range of the tape for recording primarily the desired reflected signals over a broad frequency range. Replays of the magnetically stored data were made through filter pass bands designed to emphasize particular reflection events when the need arose.

Extrapolation of Test Results over Prospect

The sequence of tests were conducted at several shotpoint locations distributed along a two-mile line. There is always a question of how applicable the results of tests conducted in a very localized area will be to the design of a suitable recording technique for the entire prospect. It is a commonplace observation that in a poor record area, the response will vary over wide ranges.

In this instance the tests served to provide a description of the problem and methods of solution in one location. Once accomplished, it was necessary only to keep track of the variation in noise characteristics to guide the modification of the initially-developed recording technique as needed. The changing conditions were followed by conducting very abbreviated tests with an experimental arrangement of the type illustrated in Figure 7. Such tests required very little production time. Operationally, the only additional work required was that involved in laying out a test cable alongside one-half of the spread arrangement being used and making the necessary recordings. The abbreviated tests were conducted when the technique adopted failed to produce the predicted result or when the driller's logs indicated a marked variation in near-surface conditions. Such tests could be interpreted in a meaningful fashion by relating the observations to the experiences developed in the initial and more comprehensive tests.

RESUME

To consider the nature of an exploration program designed to investigate a suspected anomalous feature, conferences attended by oil company geologists, geophysicists, and service company geophysicists were held. The objective of the proposed exploration program was clearly specified by the oil company. In studying the contribution toward the realization of the objective expected from seismic methods, it was observed that the data obtained in prior surveys in the prospect were inadequate to meet the new requirements. A review of these data and rele-

vant geologic conditions indicated that by means of a carefully executed experimental program the cause of the poor records could probably be successfully discovered and suitable recording techniques could be developed. The quality of data needed was specified, and a time schedule was set for the investigation of the problem and the evaluation of proposed solutions. This entire procedure constituted a good example of the objective approach to exploration advanced by Agnich and Dunlap (1959).

Experimental tests were subsequently carried out, and the investigation and evaluation phase was completed in three production days. The test results indicated that the poor record quality in the area was attributable chiefly to the destruction of the reflection continuity by relatively strong surface and near-surface waves generated by and propagating outward from the exploding charge. Because of the time range over which it was desired to secure data, the device of offsetting the shot was not a possible technique for improving the signal-to-noise ratio. Owing to the apparent wave length separation between the reflected signals and interfering noise, wave length filtering by means of suitable seismometer and shot patterns and compositing through data processing methods provided a major increase in record quality. Use of wave length filtering permitted the recording of a broad frequency range of reflected signals on magnetic media.

Utilization of the techniques developed from the tests yielded results sufficiently improved from those obtained in an earlier survey to warrant a continued pursuit of the exploration objective. A sample of the reflection data recorded in the vicinity of the tests is shown in Figure 17. The top two seismograms displayed in Figure 17 and the seismograms displayed in Figure 2 were recorded at common surface positions.

COMMENTS ON GENERAL EXPERIENCES WITH PROCEDURE

The general analytical method of investigation, of which this case history is a specific example, has been used a number of years for studying record quality problems in many prospects around the world. The investigating procedure has been found to be a practical and generally useful means for discovering the nature of the problems and for estimating what improvement can be accomplished by practical means. On some occasions the answer to such a study has been that the problem probably cannot be solved by means of existing techniques or that the solution is too expensive in terms of anticipated rewards. At the other end of the scale of difficulty, problems were encountered which could be solved in several ways, and the task was to develop the most economic recording geometry from possible alternatives.

Experience has shown that the near-surface and surface waves commonly grouped under the general term of "ground roll" frequently constitute the dominant interfering noise and that these waves exhibit peaked wave length distributions characteristic of the near-surface materials. This latter condition would be expected since the characteristics of these waves are uniquely related to layering

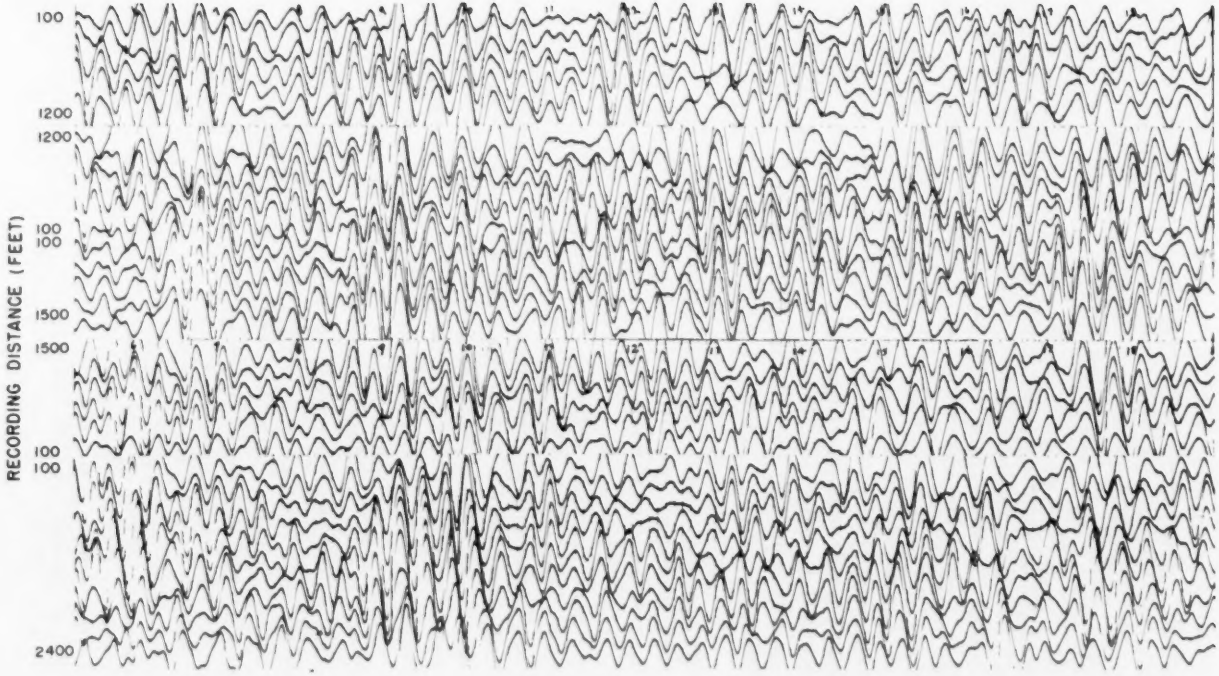

FIG. 17. A sample of the reflection data recorded in the vicinity of the test area. Permit restrictions at these four shotpoints ruled out use of optimum charge size and pattern holes. Seismograms were recorded with one hole, 1¼ pound charges, and 18 seismometers per group. The top two seismograms were obtained at same location as those displayed in Figure 2.

sequence, velocities, densities, and other physical properties of the shooting medium. Again, when coherent noise waves are the dominating interference, experience has shown that better seismic data can be obtained when the design of the recording technique is based on the special character of the noise determined from tests and sampling procedures than when the design is based on more general assumptions.

The amount of testing needed to keep track of changing conditions depends upon the difficulty of the problem and the rate of change in the physical properties of near-surface materials. A record quality problem characterized by high intensity noise coupled with complicated and rapidly changing subsurface structural conditions may require a sampling of the noise at every profile or at alternate profiles. Measures of noise intensities obtained at such close sampling intervals can be represented on a noise intensity contour map. The behavior of the contours on such a map provides a criterion for deciding whether disappearance of a reflected band of energy is attributable to increased noise intensity or to a rapidly changing structural condition. Whether or not such procedures are worth the effort depends specifically on the estimated value of achieving the exploration objective.

Frequently the noise consists of both coherent boundary waves and wave groups arriving in random directions. Such random waves may be largely disturbances from secondary sources set up by the impinging of the initial near-surface waves upon randomly located-near-surface inhomogeneities. In such situations it is important to establish which noise is dominant in the time range under investigation. In those cases in which both types of waves are sufficiently damaging, it may become necessary to construct two dimensional patterns having specified responses for particular directions of arrival. By the use of a suitably designed shot array, either horizontally or vertically distributed charges, it is often possible to reduce the energy traveling outward in the primary noise wave and hence reduce the strength of the potential secondary sources.

ACKNOWLEDGEMENTS

The author expresses his appreciation to the client company which generously permitted use of the data and to Geophysical Service Incorporated for permission to publish the paper. The author wishes also to give recognition to Mr. K. E. Burg and his staff for valuable help and suggestions.

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DISCUSSIONS AND COMMUNICATIONS

PRELIMINARY REPORT

A STRATIGRAPHIC SEISMOGRAM*

CARL H. SAVIT†

To the present time, the great bulk of seismographic exploration has, perforce, been devoted to obtaining subsurface structural information. Stratigraphic information has not normally been forthcoming except insofar as stratigraphy could be deduced from structure. What little direct stratigraphic information was available came from velocity data resulting from refraction surveys or delta-tee analyses of reflection results. Both these types of velocity-derived stratigraphic information suffer from lack of resolving power.

Clearly, exploration seismology needs a procedure with the structural resolving power of the reflection method while yielding a high content of stratigraphic information. While seeking this goal, geophysicists are also keenly aware that a major fraction of the information content of seismic signals is left unused.

This report concerns a technique which attempts to use some of the previously unused information in seismic signals to produce a record which may be correlative with some aspects of stratigraphy. The Summarizer, the apparatus used in this study, is an invention of Dott. Ing. Eduardo Merlini of AGIP Mineraria.[1]

Technique

Basically, the Summarizer produces an output which is a function of the total energy received by a seismometer spread. Under ordinary circumstances, the Summarizer record is produced simultaneously with a conventional reflection record.

Although this process can be carried out directly in the field, the results to be reported here were obtained from tape recordings. Broad-band tapes recorded with loose AVC were used. Normal-moveout and static corrections were applied before the Summarizer operation. The Summarizer itself accepts the conventional broad-band signal for each seismometer group, controls its amplitude by means of a controllable fixed-rate expander, and converts the signal to a function of energy. "Energy" signals from all groups are then summed and integrated with respect to time.

Obtaining noise suppression by summation and integration rather than by sharp filtering, the Summarizer produces an output with an unusual amount of

* Presented at the twenty ninth Annual International Meeting, November 10, 1959. Received by the Editor November 8, 1959.

† Western Geophysical Company of America, Los Angeles, California.

[1] Merlini, E., 1959, Un nouveau dispositif auxiliairie dans la recherche sismique, Geophysical Prospecting, v. 7, p. 129.

"character." Amplitude ranges impossible in conventional reflection records are characteristic of the Summarizer record.

Research presently under way is principally concerned with an attempt to determine the extent to which the character of the Summarizer output can be correlated with stratigraphy.

Experimental Results

Two examples are presented to demonstrate results so far produced under conditions of known stratigraphic change.

One example from California (Figures 1–4) involves a line connecting two wells. Both wells are dry but the objective zone at location 1 is a well-developed sand of considerable porosity. At the other well, location 13, this sand, while present, is silted up almost completely. A zone of high energy on the Summarizer section is present at the proper time at location 1. Between the two wells, this energy band fades out. In this particular instance, a conventional reflection section also shows the same energy band disappearing. A close comparison of the Summarizer and filtered reflection sections discloses, on the other hand, that the behavior of the energy traces cannot consistently be deduced from that of the filtered section. While this example does not yield a firm conclusion on the value of the Summarizer, it does exhibit the desired type of results and serves to illustrate some of the difficulties inherent in the experimental program.

Figures 5 to 8 present another example of Summarizer experimental results. At this location in Western Canada, a line is available through a stratigraphic-trap oil field. Two producers and one dry hole are on the line.

Relatively high energy characterizes the Summarizer traces at the level of the producing sand within the field. At location 1, near the dry hole, the energy disappears. Electric logs and cores indicate that the target sand has become a nonporous, sandy limestone at the dry hole.

Reflections in the zone of interest corresponding to the energy found on the Summarizer section may be detected on a filtered section. Those reflections are, however, neither continuous nor, in most cases, pickable. Furthermore, if any correlation exists between the behavior of the Summarizer traces at the target level and that of the filtered reflections, it is certainly not apparent.

Research in Progress

Investigations are presently under way to determine experimentally and theoretically the effects of moveout, irregular weathering patterns, spread dimensions, and other field conditions on the Summarizer output. Preliminary results indicate that the output trace is, in general, relatively insensitive to irregularities in moveouts of the order of ten milliseconds. Even this conclusion is apparently dependent upon the natural frequency content of the input energy and upon the integration interval.

Experiments are, therefore, projected or under way to examine the effects of

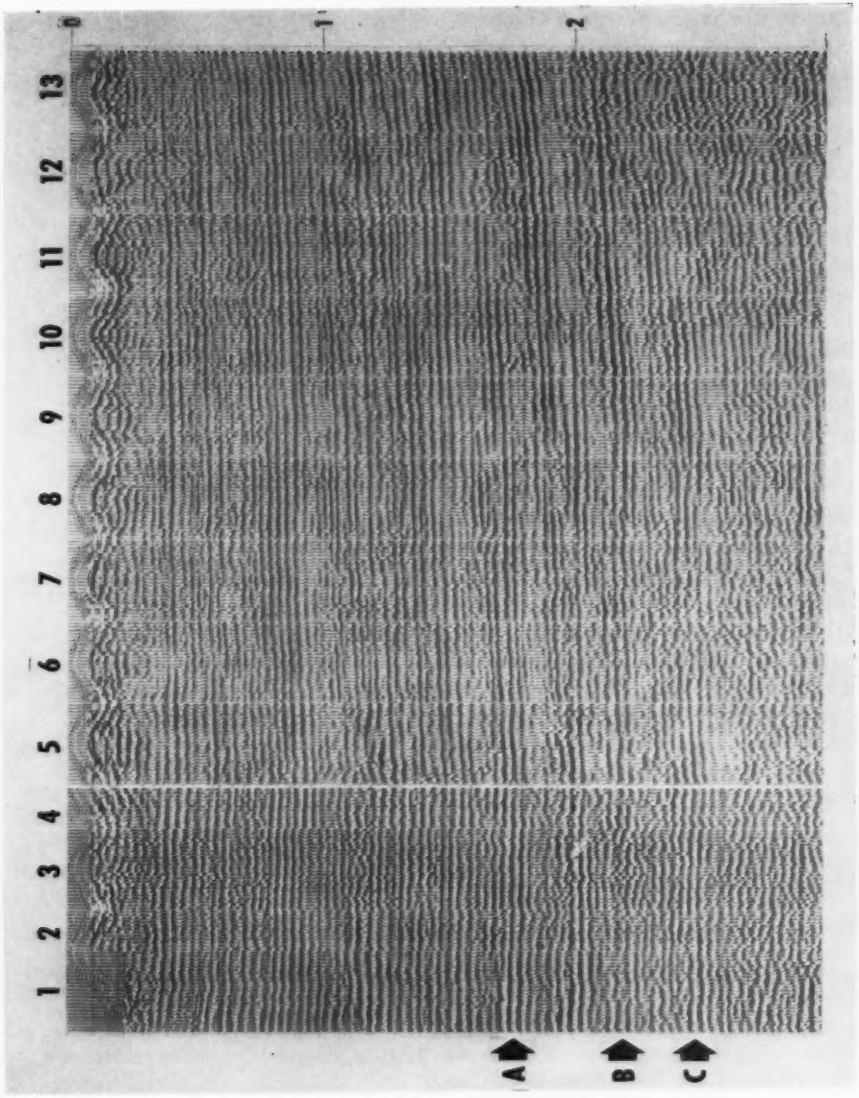

FIG. 1. Record section from California. Wells are present at locations 1 and 13. Break in the section between locations 4 and 5 indicates a 90° change in bearing.

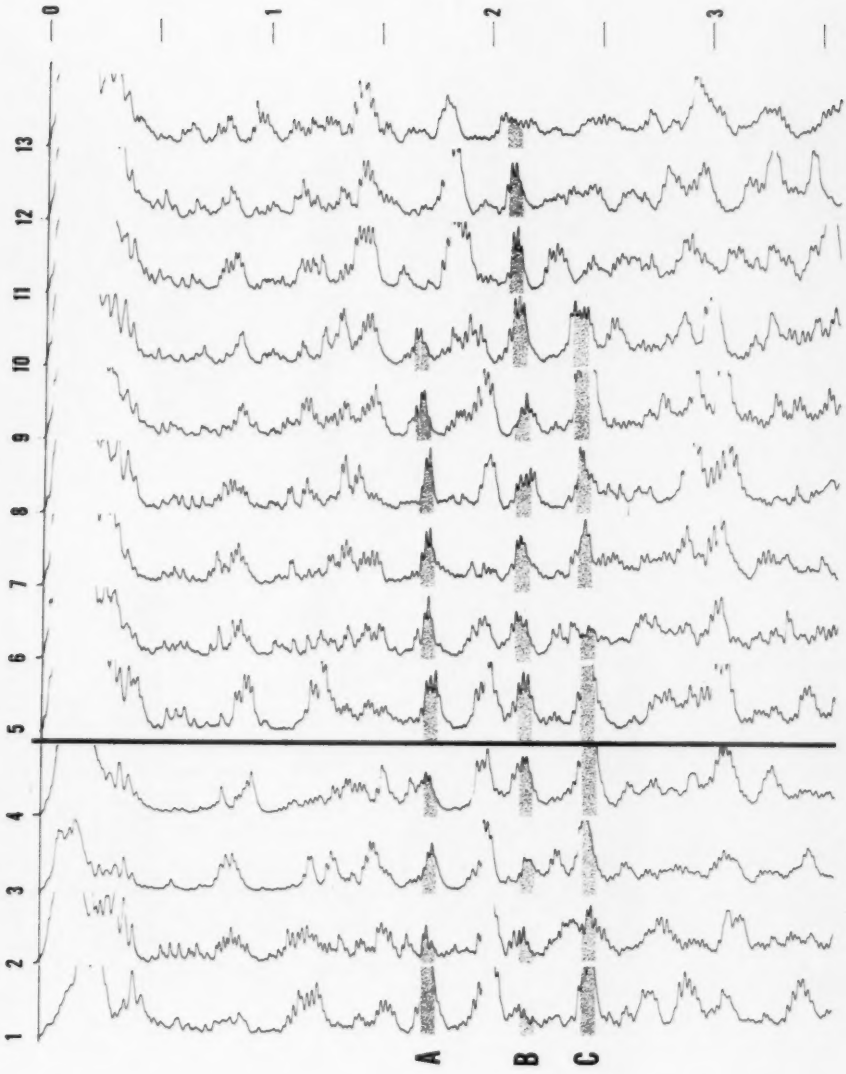

FIG. 2. Summarizer section for the same California line. Horizons are labeled to correspond with those of Figure 1.

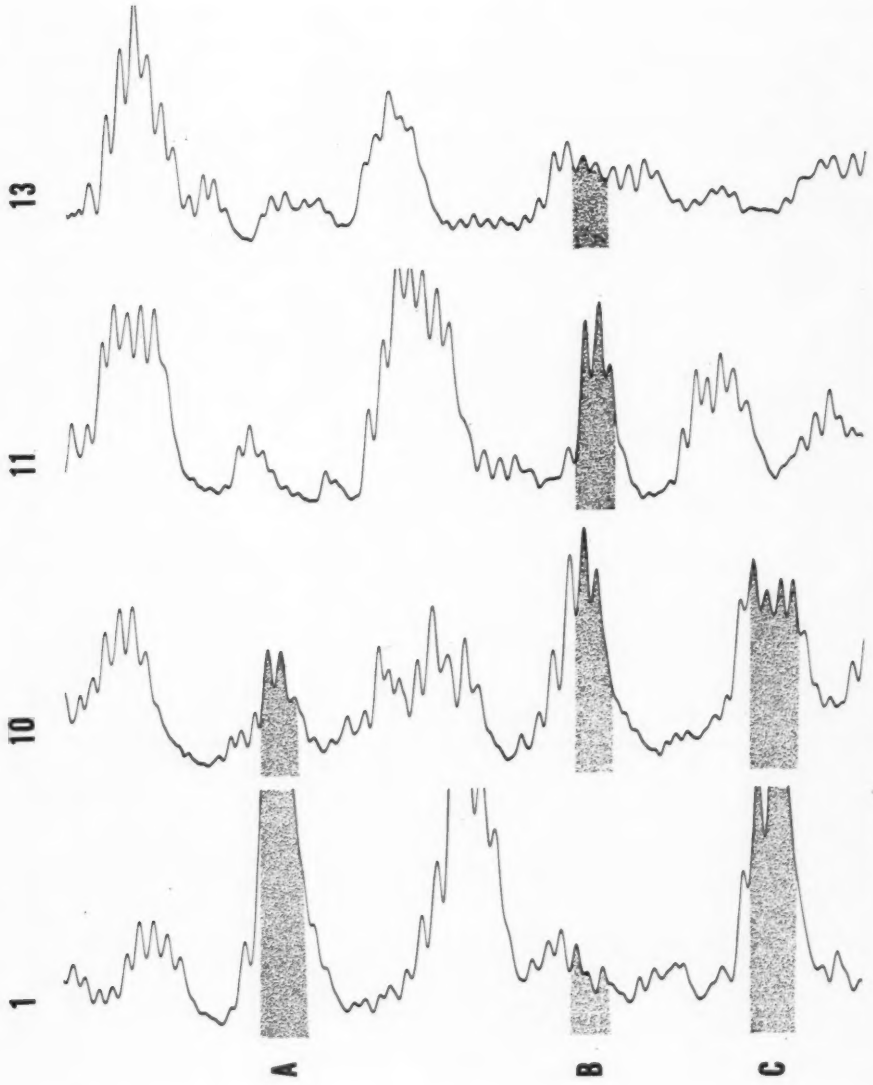

FIG. 3. Enlarged detail of four Summarizer records of Figure 2. Of particular interest is the disappearance of energy band *C* between locations 10 and 11.

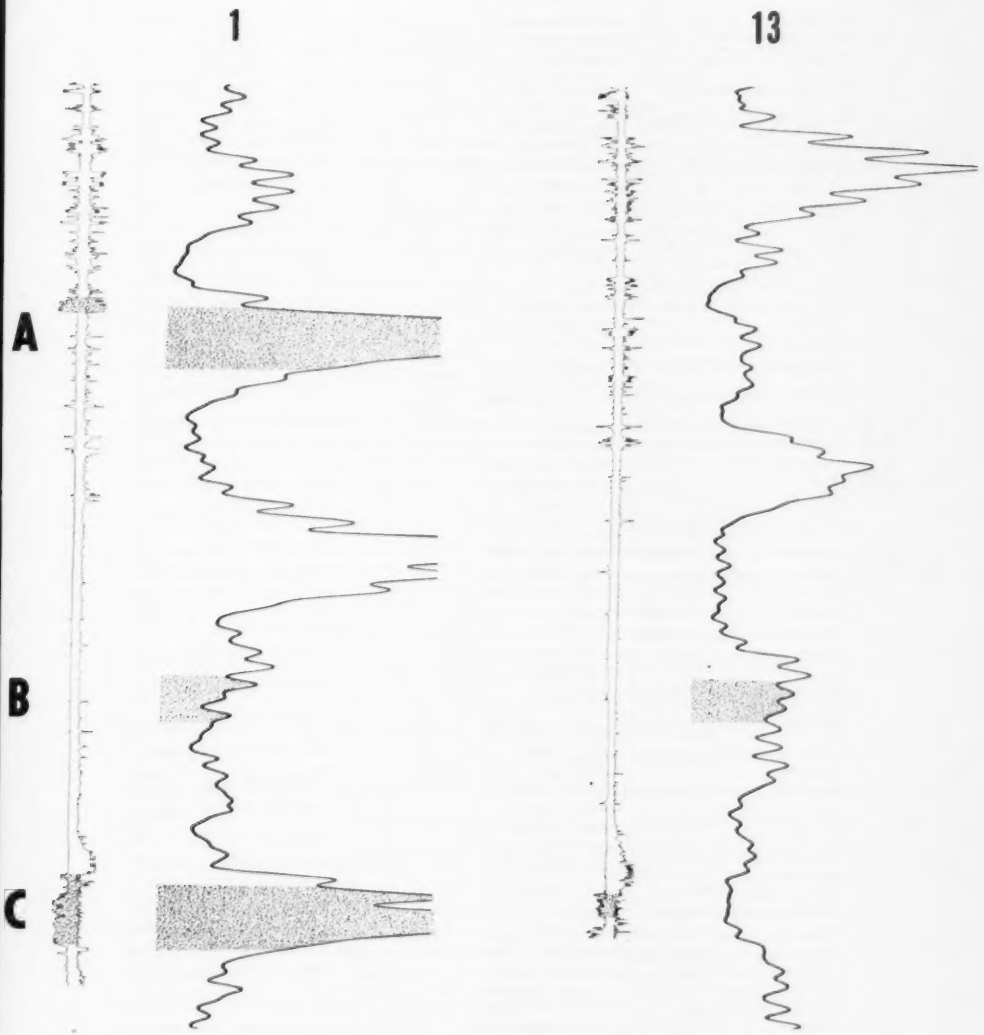

FIG. 4. Summarizer traces, locations 1 and 13, compared with corresponding *E* logs. *E* logs and Summarizer records have been reduced to approximately comparable scales. Horizon *C* has changed from a clean sand at location 1 to shale and siltstone with some thin sands at location 13.

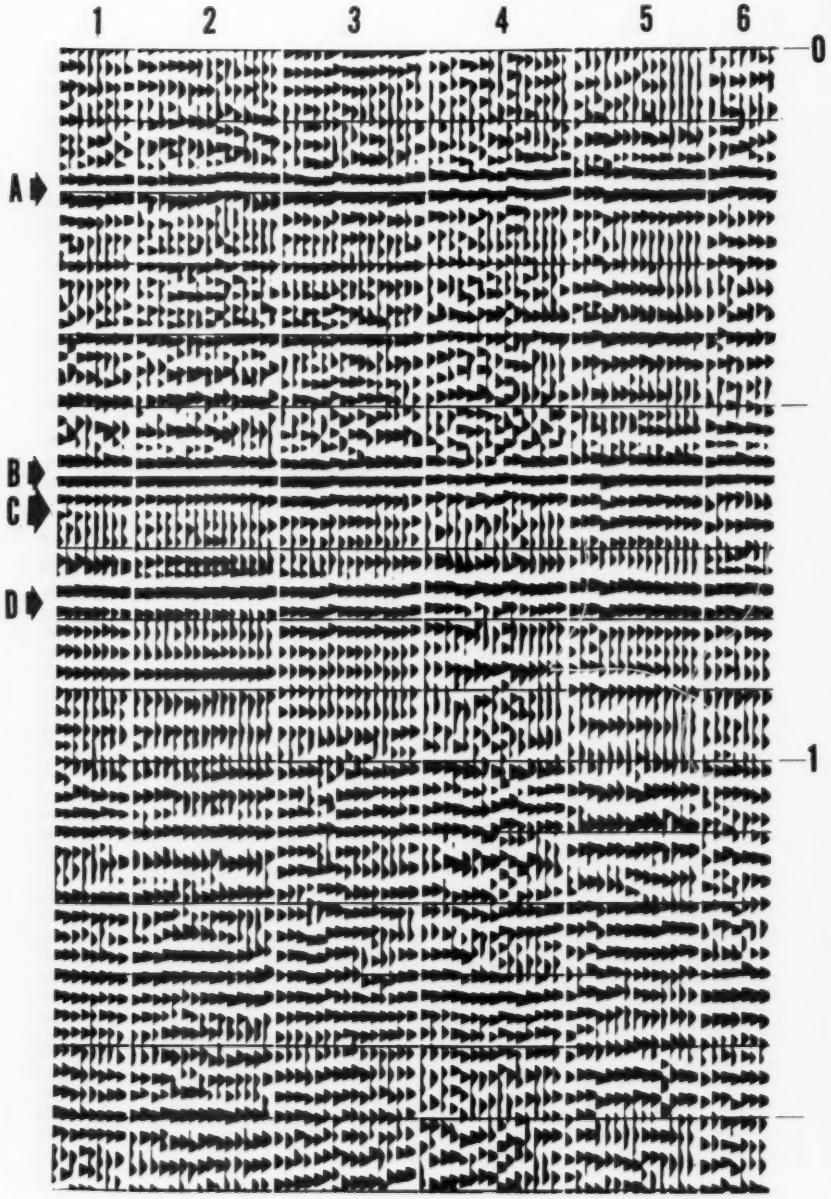

FIG. 5. Record section from Western Canada. Times are measured from an arbitrary datum plane.

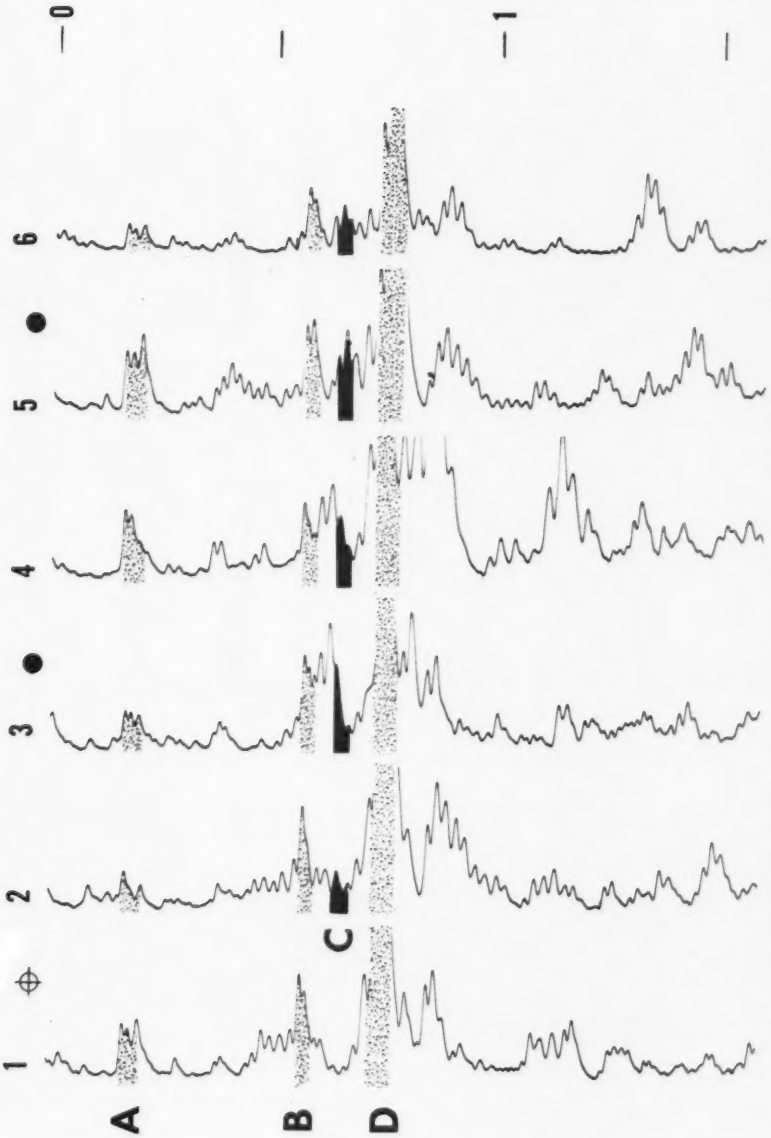

FIG. 6. Summarizer section for the same Canadian line. Three wells on the line are shown in their correct locations.

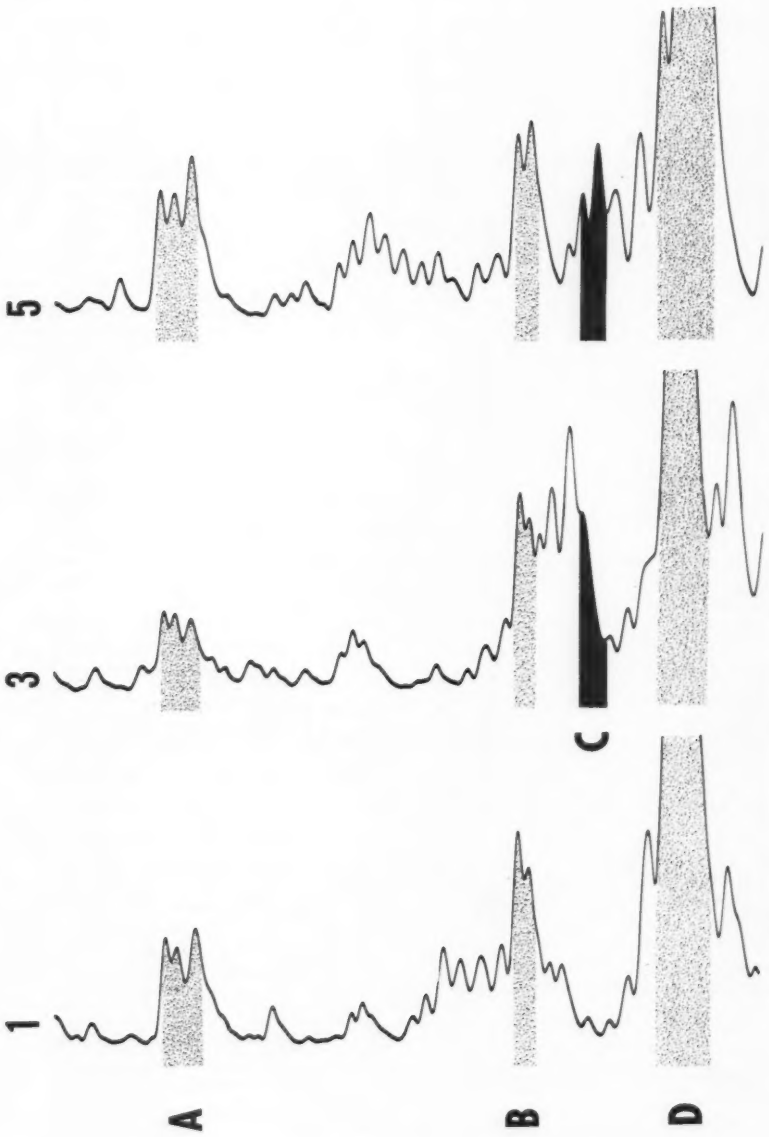

FIG. 7. Detail of Summarizer traces shown in Figure 6. Horizon *C* is represented by a high energy level at stations 3 and 6. At station 1, this horizon is completely absent.

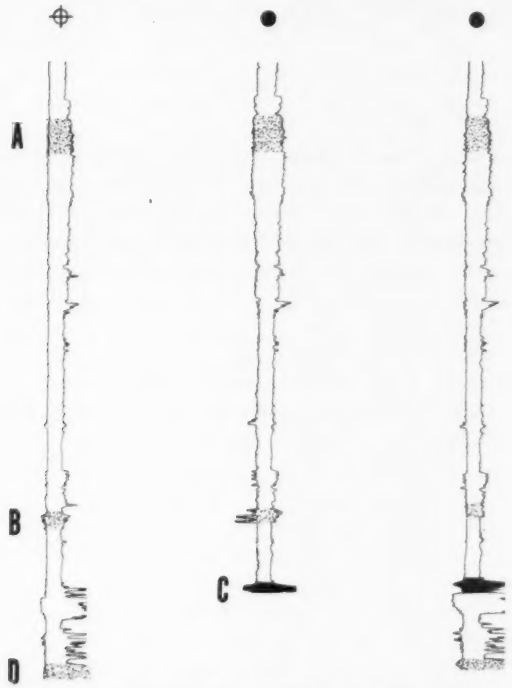

FIG. 8. Electric logs for wells shown in Figure 6. Horizon *C* is a porous sandstone at the two producing wells. At the dry hole it is a sandy limestone.

various natural seismic frequency patterns and of variations in instrument parameters.

Another, and possibly promising, line of investigation is the application of the Summarizer to very poor or NR record areas to see if this new function of seismic energy may produce useful information.

Underlying all of these programs is the basic necessity of processing many surveys in known and semi-known areas to build up a backlog of experience in the interpretation of this new mode of seismic data processing.

Acknowledgements

Appreciation is expressed to Dott. Ing. Eduardo Merlini, AGIP Mineraria, S.p.A., Richfield Oil Corp., and Pan American Petroleum Corp. for their wholehearted cooperation in the research program; to Western Geophysical Company for permission to publish this report; to Mr. E. T. Gaulke and Mr. Mark Holzman who so ably carried out the experimental procedures; and to Miss Dorothy Stark who prepared the illustrations.

COMMENTS ON "FREQUENCY ANALYSIS OF SEISMIC PULSES," SECTION I (THEORY)*

R. L. SENGBUSH†

It is amazing that Fourier analysis is still misunderstood 137 years after Fourier. The periodic time-waveform and its frequency spectrum are not too troublesome. It is in going from the periodic to the transient that causes the difficulty. At the risk of being obvious, let me outline the basis of the analysis.

Beginning with the periodic time-waveform, if a function of time can be represented by

$$p(t) = p(t + T),$$

the function is periodic in time with a period T. Fourier theory then states that the function (subject to certain well-known restrictions) can be written as a series of discrete cosine waves

$$p(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(\omega_n t + \phi_n),$$

where

$$\omega_n = \frac{2\pi n}{T}.$$

These harmonics have discrete frequencies n/t, where $n = 1, 2, 3, \cdots$. Each harmonic has an amplitude A_n and a phase ϕ_n. The coefficients A_n (including A_0) and ϕ_n constitute the amplitude and phase spectra of the time waveform. The spectra are functions of frequency. They describe the function $p(t)$ in the frequency domain.

Now consider a transient function. It never repeats itself. Thus, a series of discrete cosine waves cannot represent the transient because the series must contain a fundamental; and the fundamental has a frequency $1/T$ that causes the series to produce a repeating function with period T. One is forced in the transient case to use continuous amplitude and phase spectra. The continuous spectra are continuous functions of frequency. They describe the transient in the frequency domain. To say that "a transient pulse does not have the property of frequency" is incorrect.

However, transients can be analyzed by considering them to be periodic, as has been done in this paper. A transient function, $q(t)$ having measurable amplitude for a time duration τ, can be considered to be a repeating function outside the

* Photomechanical Method of Frequency Analysis of Seismic Pulses, by B. F. Howell, A. B. Andrews, and R. E. Huber, Geophysics, v. 24, p. 692–705.

Received by the Editor October 20, 1959.

† Socony Mobile Oil Co. Inc., Field Research Lab., Dallas, Texas.

interval τ. Thus, inside the interval, $q(t)=p(t)$, whereas outside the interval, $q(t)=0$ and $p(t)=p(t+T)$. Consequently, a harmonic series having a fundamental frequency $1/\tau$ can describe the transient inside the interval.

Now if the transient is considered to be periodic with period $T>\tau$, a harmonic series with fundamental frequency of $(1/T)<(1/\tau)$ will describe the transient. If $T\neq\kappa\tau$, where κ is an integer, no frequency that was present when τ was the period will be present when T is the period. The function becomes a transient when T increases without limit. Then the fundamental frequency approaches zero. Discrete spectra cannot possibly describe the transient, and continuous spectra are required.

Another interesting fact that results from increasing T from τ to infinity is that the amplitude at a given frequency decreases as T increases, and in the transient case the amplitude at any given frequency is zero. Thus, it is necessary in the transient case to consider amplitude density instead of amplitude.

In the periodic case, if the amplitude coefficients A_n are multiplied by the period T, the coefficient A_nT will be independent of T. In the limit as $T\rightarrow\infty$, and $A_n\rightarrow 0$ as a consequence, the coefficient A_nT becomes the amplitude density. The coefficients A_nT have value at discrete frequencies, whereas the amplitude density has value at all frequencies. The values of A_nT for the harmonics in the periodic case are identical to the values of the amplitude densities for these same frequencies in the corresponding transient case.

It would appear offhand that increasing T would give more information about the spectrum of the transient, but this is not true. The Sampling Theorem in the frequency domain shows that all information contained within the spectra of the transient is also contained within the spectra of its periodic counterpart having a period τ. In other words, the amplitude density of frequencies intermediate to n/τ, which force the periodic function to zero outside the interval τ and contribute nothing within that interval, are not arbitrary, but are perfectly well-known once the $A_n\tau$ coefficients are determined by analysis of the periodic function. It merely requires convolution of the discrete spectra with the function sine ft.

The final point concerns the author's observation in Figure 1 that discrete sampling of the time waveform cannot distinguish between the curved and solid curves which pass through the same sample values. However, if a function is sampled in accordance with the Sampling Theorem in the time domain, that is, if the samples are taken at intervals of $\Delta t=1/2f_0$ where f_0 is the highest frequency having measurable amplitude; the values of the sample points will completely specify all intermediate values. In other words, the intermediate points are not arbitrary. They can be obtained by convolving the sampled function with the function sine $2f_0t$.

In a numerical calculation of the Fourier spectra, it is imperative that the sampling of the time waveform be done properly. Then the resulting spectra will characterize the sampled waveform, which in turn completely specifies the continuous waveform.

AUTHOR'S REPLY

B. F. HOWELL, JR.*

Because Fourier analysis is so well known, no attempt was made in the paper to go into detail on its theory. Sengbush's concept of amplitude density in the case of integral analysis is clearer than the way this process is described in the paper.

His principal objection appears to be to the statement that "a transient pulse does not have the property of frequency." This is in part a question of semantics and in part a question of how one views the problem. Frequency was used in our statement in the physical sense of number of times something is repeated per unit of time. The word is also often used in an analytical sense to describe the repetition rate of a mathematical model which may be used to describe a physical reality. The mathematical model can have the property of frequency in both senses, as in the case of a Fourier integral, because the model is a sum of parts which are repetitive. From my viewpoint, the real pulse has the property of frequency only in the analytical sense, as it is not in general a sum of parts.

The value of the mathematical model is that it can be used to describe the physical transient in a way which breaks it down for comparison with other physical pulses which may look quite different. It does this by applying to the transient its own property of frequency. Actually, Fourier analysis is only one of many possible means of describing a pulse. (For instance one can approximate any pulse by a sum of step waves.)

In practice one never carries out a complete Fourier analysis, either harmonic or integral, but only a limited number of terms. Any desired degree of accuracy can be obtained by using sufficient terms. The significant point is that the analysis is only a means of describing the pulse to a limited accuracy. No matter how thorough the analysis, it never becomes the pulse itself.

Sengbush's comment on the need of close sampling is a different way of putting one of the things which the paper was intended to show: specifically that the accuracy with which a pulse is described depends on the method used to describe it. Both the photomechanical and Fourier methods are approximations. The photomechanical method has inherent inaccuracies besides any inaccuracies introduced by the incompleteness of the spectrum. However, for the same amount of time and effort, which in practice is of vital importance, it has the advantage that it gives more terms of the Fourier analysis. The trouble with Fourier analysis is not that it can not give a good approximation, but that for the limited number of terms often obtained and with the not-always-ideal choice of a fundamental period or periods for the analysis the end-result may lack needed detail. The method described here is cheap, fast, and gives as much or more accuracy as the same time and money spent on Fourier analysis. Where extra time and cost are justified and more complex equipment (e.g. high-speed computors) are conveniently available, more refined methods of analysis should be used.

* Received by The Editor November 17, 1959.

DISCUSSION ON THE ELECTROSEISMIC EFFECT*

EUGENE KINDIJ†

I would like to offer the following comment on the paper *The Electroseismic Effect* by Martner and Sparks in the April 1959 issue of GEOPHYSICS.

This article offers some possibilities for further development of this long-known effect. As the authors mention, its immediate utility appears to be that of determining the existence of a weathered layer and the travel time through it at the shotpoint.

It seems that there is something more: Every explosion is a strong sound source. The sound in turn is a continual change of over and underpressure. This pressure propels the fluid through the capillaries, in our case through the permeable formation. According to the Helmholtz law an electromotive force is created if a pressure is applied on the capillaries. Therefore, the amplitude of the electroseismic effect should serve as a measure of the amount of the weathered layer that is permeable. If the layer would be of a compact mass, i.e., without permeability then no electroseismic effect should be involved. On the other hand, if the weathered layer is very permeable, a large electroseismic effect should be present.

The evidence of Figure 7 of the Martner and Sparks paper clearly indicates that the effect, first noted when the wave front is remote from the electrode, reaches maximum amplitude when the wave reaches the electrode. However, a varying permeability in the weathered layer would have an influence also on the amplitude.

This suggests that an application of this method might be made to determination of permeability in formations other than the weathering zone. The first attack might be on cores. An acoustic source applied on the core would create potentials which could be measured. The measured amplitudes should be directly related to permeability.

While the purpose of such a study would be to make possible the continuous measurement of permeability in bore holes, the weak acoustic sources presently available would hardly be likely to give measurable electrical potentials.

This short comment is written to emphasize the importance of this effect and to suggest further research.

* Received by the Editor July 11, 1959.

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PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,901,687. W. M. Barrett. Iss. 8/25/59. App. 9/30/50. Assign. Engineering Research Corp.

Method and Apparatus for Ground-Wave Transmission and Reception of Radio Waves. A method of radio-wave prospecting in which the transmitter is inductively coupled to two series-tuned circuits connected in series with their common terminal and each end terminal connected to spaced ground electrodes and with the time phase of the voltages applied to the electrodes adjusted to correspond to the space phase between the electrodes in the earth, a similar pick-up system being used as a receiver whose current is indicated and observed at various locations.

U. S. No. 2,901,688. W. M. Barrett. Iss. 8/25/59. App. 2/10/54. Assign. Engineering Research Corp.

Method of Exploring the Earth with Electromagnetic Energy. A method of radio-wave prospecting in which the transmitter propagates constant frequency waves into the air-earth interface at substantially grazing incidence so that part of the wave is refracted downward, and observing the electromagnetic field with a receiver at points spaced from the transmitter from 1.4 to 2.7 times the depth of subsurface reflectors and observing anomalous variations in the electromagnetic field.

U. S. No. 2,901,689. W. M. Barrett and G. Baker. Iss. 8/25/59. App. 1/23/57. Assign. Engineering Research Corp.

Method of Exploring the Earth with Electromagnetic Energy. A method of radio-wave prospecting in which the electrical properties of the surficial earth material at the transmitter location are measured and the refraction index computed, and either the angle of incidence or the frequency of the transmitted wave is adjusted so as to propagate radio waves into the earth at the optimum angle of incidence to obtain maximum energy into the ground.

GRAVIMETRIC PROSPECTING

U. S. No. 2,899,826. L. J. B. La Coste. Iss. 8/18/59. App. 1/25/56. Assign. La Coste & Romberg.

Leveling Means for Gravity Meters or the Like. A damping arrangement for a stabilized mounting for a gravity meter in which the meter is hung on a long gimbal-supported pendulum which is given an opposing horizontal motion in response to signals from tilt-direction indicators carried on a plate attached to the top of the pendulum.

U. S. No. 2,899,828. L. B. Lynn. Iss. 8/18/59. App. 10/18/55. Assign. Westinghouse Electric Corp.

Stabilizing Apparatus. A gyro-stabilized system in which small precessions of the gyro are electrically or mechanically integrated and applied to the control system.

MAGNETIC PROSPECTING

U. S. No. 2,891,216. F. X. Linder. Iss. 6/16/59. App. 1/16/56. Assign. U.S.A.

Compensator for Magnetic Detection Equipment. A system for compensating an airborne magnetometer for noise originating in the airplane and having two spaced aligned magnetic detectors in the fuselage of the airplane, one detector being close to the disturbance and the other farther away and with the signal from the first detector attenuated and combined in opposition to the signal from the second detector.

† Gulf Oil Corporation, Patent Department, Pittsburgh, Pennsylvania.

U. S. No. 2,891,502. J. L. Cochran, Jr., N. B. Michel, and R. A. Robinson. Iss. 6/23/59. App. 1/28/57.

Automatic Degaussing Control System. An automatic degaussing system using three orthogonal coils with separate current controls and having gyro-actuated roll, pitch, and heading transmitters feeding into a computer that derives component signals that are combined with each other and with signals representing the ship's permanent magnetization to control the three current generators.

U. S. No. 2,899,637. J. H. Stein. Iss. 8/11/59. App. 12/16/55.

Apparatus for Cancelling Turn and Yaw Noise in a Magnetometer. A system for compensating an airborne magnetometer for the effects of turn and yaw when moving in a magnetic field gradient and in which the magnetometer signal is differentiated with respect to time and combined with a compensating signal proportional to the instantaneous direction of motion, the compensating signal being obtained from a pendulum-mounted second magnetic element.

U. S. No. 2,900,595. C. L. Mengel and D. P. Miles. Iss. 8/18/59. App. 8/31/55.

Magnetic Field Detector. An airborne system for detecting an anomaly in the earth's magnetc field in which one airplane transmits two microwave radio signals, e.g. 30,000 megacycles and 60,000 megacycles, which are received on a second airplane and combined with signal from a local oscillator to produce if signals whose phase relation is observed, one of the transmitted frequencies lying in an atmospheric absorption band that is highly sensitive to changes in ambient magnetic field.

RADIOACTIVITY PROSPECTING

U. S. No. 2,897,368. H. T. F. Lundberg, R. W. Pringle, K. I. Roulston, and G. M. Brownell. Iss. 7/28/59. App. 3/18/54.

Aerial Geophysical Exploration with Scintillation Spectrometer. An airborne radioactivity prospecting system using a scintillation type detector with photomultiplier, amplifier, and pulse height discriminator, and also a pulse integrator, and recording the output of the integrator and of the various scaling devices connected to the analyzer.

U. S. No. 2,898,497. T. R. Cartmell and J. F. Gifford. Iss. 8/4/59. App. 2/8/55. Assign. U.S.A.

Airborne Radiation Detector. A detector for continuously measuring radioactivity of atmospheric air and having a pair of counters one of which has a lamp to induce circulation of air through the counter and whose output is compared with that of a second counter in a radiation-free location.

SEISMIC PROSPECTING

U. S. No. 2,889,000. D. Silverman and R. E. Fearon. Iss. 6/2/59. App. 9/13/51. Pan American Petroleum Corp.

Seismic Surveying. A system for improving the signal-to-noise ratio in seismic prospecting in which geophone signals arising from waves traveling over different paths are repeatedly multiplied with a slowly-varying time phase between them and the product integrated over a relatively long time interval and the integral plotted as a function of the time displacement.

U. S. No. 2,889,776. U. Gunther. Iss. 6/9/59. App. 8/21/56. Assign. Inventa A. G. Fuer Forschung und Patentverwertung.

Method and Device for the Generation of Impulses in Electric Detonators. An impulse generator having a magnet wound with a coil and with the magnetic circuit closed by an armature, a small amount of explosive being placed at the junction of the armature and the magnet so that when a firing pin detonates the explosive the magnetic circuit is quickly broken and an impulse generated in the coil.

U. S. No. 2,890,438. T. Bardeen. Iss. 6/9/59. App. 12/8/54. Assign. Gulf Research & Development Co.

Seismometer. An electromagnetic seismometer having a radially magnetized disk-shaped magnet with a central boss that engages a cup-shaped member forming an air gap with the outer edge of the magnet, and having a coil elastically suspended in the air gap.

U. S. No. 2,890,655. M. Apstein. Iss. 6/16/59. App. 3/7/56. Assign. U.S.A.

Firing Circuit. A detonator firing circuit having one terminal of a condenser connected to the plate of a thyratron tube and the other terminal of the condenser connected to the cathode of the tube through an inductance and the detonator in parallel, firing signal being applied to the grid of the thyratron.

U. S. No. 2,890,861. C. V. Cook. Iss. 6/16/59. App. 12/31/54. Assign. Phillips Petroleum Co.

Underwater Geophysical Prospecting. A system for drilling and loading shot holes in water-covered areas in which the drill bit is sheared off by a go-devil that is retrieved through the drill pipe; the explosive charge, cap wires, and an elongated float being inserted through the drill pipe so that the pipe can be recovered.

U. S. No. 2,891,232. H. O. Benecke. Iss. 6/16/59. App. 6/28/55.

Hydrophone for Directional Listening Buoy. A hydrophone having a number of cylindrical transducers with their axes parallel and in a common plane and spaced by one-half wave length, and a plane reflector parallel to the transducers spaced behind them by one-fourth wave length.

U. S. No. 2,891,233. F. J. Crandell. Iss. 6/16/59. App. 12/22/54.

Microseismic Detection Apparatus and Particularly Geophones Therefor. A geophone having a piezo-electric crystal mounted as a cantilever and connected to a transformer in the geophone case.

U. S. No. 2,892,128. A. A. Wolf. Iss. 6/23/59. App. 6/23/54. Assign. Fidelity Instrument Corp.

Blasting Cap Electric Firing System. A blasting machine in which a manually powered generator charges two condensers and upon reaching firing voltage also trips a relay that disconnects the condensers from the generator and connects one condenser to a second relay whose operation connects the second condenser to the firing circuit.

U. S. No. 2,892,993. E. F. Kiernan. Iss. 6/30/59. App. 6/2/53.

Ultrasonic Probe. A high frequency sound field detecting device having thin conducting leads on a thin mica wafer with a notch across which a fine wire is mounted between the leads.

U. S. No. 2,894,596. T. Flatow and C. H. Carlisle. Iss. 7/14/59. App. 10/5/55. Assign. Jersey Production Research Co.

Method of Determining Seismic Reflecting Subsurfaces. A seismic prospecting system in which a number of spaced shots are fired and reflections recorded as separate traces from spaced geophones, and the traces of the various shots to each geophone subsequently added with variable phase relation until the combination of phase relations is found that maximizes the resultant summation.

U. S. No. 2,894,797. R. A. Kirby, C. S. Clay, Jr., and H. B. Ferguson. Iss. 7/14/59. App. 11/30/54. Assign. Jersey Production Research Co.

Recording System. A variable-density pen-type recording system in which an electromagnet vibrates a diaphragm that is connected to a wide pen to move it toward and away from the record medium, the electromagnet being connected to a circuit that converts the signal to square wave pulses.

U. S. No. 2,895,014. L. H. Johnson. Iss. 7/14/59. App. 7/6/53. Assign. United Geophysical Corp.

Magnetic Recording Head-Moving Mechanism. A mechanism for moving the heads of a magnetic recorder by means of adjusting screws driven through flexible cables and arranged so that movement of each head carries along and maintains the spacing of all succeeding heads.

U. S. No. 2,897,351. B. S. Melton. Iss. 7/28/59. App. 3/2/53.

Apparatus for Testing for the Existence of Signals in the Presence of Overriding Noise. A system for identifying reflection signals in the presence of noise in which the traces are separately recorded on devices for introducing various amounts of delay and signals from the variously delayed pick-ups are combined in a series of coincidence detectors whose outputs are separately integrated and recorded.

U. S. No. 2,897,476. M. B. Widess. Iss. 7/28/59. App. 10/5/55. Assign. Pan American Petroleum Corp.

Seismic Signal-to-Noise Ratio. A selective trace compositing system in which a gate is connected between the playback unit and the summation unit with each gate controlled by the signal from an integrator and comparator so as to eliminate from the summation over any time interval those traces that have excessive noise.

U. S. No. 2,897,755. G. M. Pavey, Jr. Iss. 8/4/59. App. 5/21/58. Assign. Marine Research Co.

Ring Actuated Locking Electrode for a Towed Firing Line. A ring-latching mechanism for the end of a firing line used in marine seismic operations and with the latch spring arranged so that the oncoming ring first depresses the latch to release the preceding ring and is then caught on the latch so that its charge can be fired.

U. S. No. 2,898,084. J. E. Eckel and J. M. Camp. Iss. 8/4/59. App. 12/16/54. Assign. Jersey Production Research Co.

Seismic Shock Source. A device for initiating a seismic impulse from the bottom of a shot hole without removing the drill string and having a telescoping section in which air is compressed by downward force and which releases a short known time after the drill string is raised off bottom, the delay being provided by flow of fluid through a small opening in a check valve.

U. S. No. 2,898,574. E. M. Palmer. Iss. 8/4/59. App. 6/20/56. Assign. Gulf Research & Development Co.

Apparatus for Profile Presentation of Seismic Information. An apparatus for profile presentation of seismic data from magnetic records which scans the record and concurrently mechanically makes the static and dynamic corrections and photographically rerecords the records in variable-density form with correct vertical travel time.

U. S. No. 2,898,575. A. B. Hildebrandt. Iss. 8/4/59. App. 3/21/56. Assign. Jersey Production Research Co.

Geophone Assembly. A mounting for a borehole geophone in which the geophone is fastened to a shoe with two projections that contact the borehole wall, the shoe being forced outward by means of bow springs pivoted to a sliding member at the lower end of the cable.

U. S. No. 2,900,037. L. G. Ellis. Iss. 8/18/59. App. 7/15/54. Assign. Sun Oil Co.

Seismographic Exploration. A seismic exploration method in which the detectors are placed in vertical arrays in shallow boreholes and their signals recorded on separate traces from which the attitude of a reflecting horizon can be calculated.

U. S. No. 2,900,619. O. C. Montgomery. Iss. 8/18/59. App. 7/12/54. Assign. Phillips Petroleum Co.

System for Recording Time. A seismic shot firing device in which the firing circuit is coupled to the

signalling circuit through a transformer and the signalling circuit has a series rectifier and condenser that is charged during the build-up of firing current, and upon firing the condenser discharges through another rectifier to provide the shot moment signal.

U. S. No. 2,900,724. E. V. Herbert. Iss. 8/25/59. App. 2/7/56. Assign. California Research Corp.

Strataplotter. A seismic reflection plotting device in which the seismic record is mounted on a movable table under a transparent template having indices corresponding to intertrace time variations and covered by a sheet of transparent plotting paper, the record being moved to an appropriate index on the template which then indicates the correct point to be plotted.

U. S. No. 2,900,795. H. Brandt. Iss. 8/25/59. App. 10/20/55. Assign. California Research Corp.

Raising and Lowering Apparatus. A seismometer cable assembly for use in seismic operations in shallow water and having an inflatable auxiliary cable attached to the seismometer cable so that the assembly can be floated or lowered to bottom by introducing or withdrawing air at the end of the cable.

WELL LOGGING

U. S. No. 2,889,001. J. O. Ely, G. C. Summers, and F. C. Karal, Jr. Iss. 6/2/59. App. 7/28/54. Assign. Socony Mobil Oil Co., Inc.

Velocity Dependent Acoustic Velocity Correction. An acoustic logging system in which a correction is made for the effect of wall velocity on the acoustic velocity of the borehole fluid.

U. S. No. 2,889,208. G. H. Smith. Iss. 6/2/59. App. 10/8/59. Assign. Union Oil Co. of California.

Well Logging Process. A process of detecting argillaceous material in core samples or drill cuttings by contacting the sample with a non-ionic surfactant in solution and detecting base-exchange reaction by diminution of surfactant concentration in the solution.

U. S. No. 2,890,019. J. J. Arps. Iss. 6/9/59. App. 3/26/56.

Earth Borehole Logging System. A system for logging while drilling in which a stationary ribbed stabilizer unit carries armatures of a permanent-magnet type a-c generator whose current is used for the log measurement and whose amplitude is detected by rectifying the current and applying it to electrodes in a restricted channel for the drilling mud so that electrophoresis causes deposition of clay particles which increases the circulation pressure.

U. S. No. 2,890,405. R. C. Rumble and H. M. Buck. Iss. 6/9/59. App. 6/19/57. Assign. Jersey Production Research Co.

Fluid Flow Indicator and Fluid Identifier. A fluid logging device having two spaced packers with a central conduit that has a check valve opening to the space between the packers, the valve and valve seat being in an electric circuit so that when the valve is open the conductivity of the entering fluid can be measured at the surface.

U. S. No. 2,891,166. R. G. Piety. Iss. 6/16/59. App. 3/15/54. Assign. Phillips Petroleum Co.

Well Logging. A radioactivity logging system in which the detector actuates a neon tube whose flash is focussed on a photographic tape as a line transverse to the motion of the tape which is proportional to depth, so as to produce a variable-density record.

U. S. No. 2,891,215. R. E. Fearon. Iss. 6/16/59. App. 11/13/56. Assign. Electro Chemical Laboratories Corp.

Method and Apparatus for Electric Well Logging. A system for electrical logging in a cased or uncased hole in which a-c is induced in the casing by pairs of electrodes above and below an inter-

mediate measuring zone, and potential electrodes in the measuring zone are connected to amplifiers and the signal recorded.

U. S. No. 2,891,728. N. A. Schuster. Iss. 6/23/59. App. 4/2/53. Assign. Schlumberger Well Surveying Corp.

Electronic Computing Apparatus for Computing a Root or a Power of the Ratio of Two Quantities. An electronic analog computer for use in a-c electric logging in which one pick-up voltage is amplified and combined with the other pick-up voltage and the combined signal used to control the gain of the amplifier.

U. S. No. 2,892,151. J. C. Bender. Iss. 6/23/59. App. 8/10/53. Assign. Houston Oil Field Material Co., Inc.

Apparatus for Locating Anomalies in a Well Bore. A probe for locating a metal object lost in a well having an axial permanent magnet and a highly permeable core with a coil exicted by an oscillator whose frequency change caused by the presence of the object is observed.

U. S. No. 2,892,501. H. B. Boller. Iss. 6/30/59. App. 11/23/55. Assign. Schlumberger Well Surveying Corp.

Borehole Apparatus. A mechanical system for coupling the mouth pad of a side-wall sampler to the body of the instrument, the pad being held retracted by means of springs and operated when desired by means of hydraulic cylinders whose pistons force the pad outward against the formation wall.

U. S. No. 2,892,977. R. Monaghan. Iss. 6/30/59. App. 12/30/54. Assign. Well Surveys, Inc.

Differential Conductivity Pipe Testing. A system for detecting and differentiating between defects in casing and in which two sets of magnets are rotated in spaced horizontal planes inside the casing and the field is picked up by stationary coils whose outputs are combined and indicated.

U. S. No. 2,893,213. S. Soloway. Iss. 7/7/59. App. 11/22/54. Assign. Schlumberger Well Surveying Corp.

Refrigerating Methods and Apparatus. A cooling system for a radioactivity logging sonde having an evaporator that is in communication with an absorbent of the vapor so that the vapor of the refrigerant such as water is continually absorbed as by an alkaline earth oxide with formation of a stable reaction product.

U. S. No. 2,894,200. S. E. Szasz. Iss. 7/7/59. App. 10/26/56. Assign. Sinclair Oil & Gas Co.

Subterranean Interface Locator. An electrode that may be screwed into the bottom end of well tubing having an electrically-nonconducting tubular lower section carrying on its side an electrode connected by an insulated wire to a pool of mercury in an electrically non-conducting cup that extends up into the tubing, the electrode being contacted by lowering an insulated wire through the tubing to the mercury.

U. S. No. 2,894,597. C. H. Kean, F. N. Tullos, and H. C. Hougen. Iss. 7/14/59. App. 11/1/54. Assign. Jersey Production Research Co.

Acoustic Well Logging Apparatus. An acoustic impedance logging device having elongated cylindrical transducing elements of barium titanate with electrodes on their outer and inner cylindrical surfaces, and with a receiving element located between two transmitting elements.

U. S. No. 2,897,372. R. E. Fearon and J. M. Thayer. Iss. 7/28/59. App. 7/30/49 and 4/19/54. Assign. Well Surveys, Inc.

Directionally Sensitive Shallow Ionization Chambers for Neutron Well Logging. A neutron logging

system using a source of fast neutrons and a shallow ionization chamber to detect those neutrons of maximum energy and returning from the formations at an obtuse scattering angle.

U. S. No. 2,897,438. R. E. Fearon. Iss. 7/28/59. App. 4/19/54. Assign. Well Surveys, Inc.

Casing Joint Detector. An electromagnetic casing joint locator having one or more permanent magnets that are rotated on an axis parallel to the borehole axis and a coil or coils symmetrically located with respect to the rotating magnetic field to pick up asymmetry in the eddy current field

U. S. No. 2,897,440. M. M. Hawthorne. Iss. 7/28/59. App. 4/12/55. Assign. Dresser Industries, Inc.

Earth Well Casing Discontinuity Detector. A casing collar locator having a pair of axial permanent magnets with like poles facing each other and with a coaxial coil between them, the coil being connected in a vacuum-tube circuit so that the emf generated when moving past a casing joint unbalances the circuit so as to indicate signal from an oscillator in the sonde.

U. S. No. 2,897,478. G. C. Summers and W. Gravley. Iss. 7/28/59. App. 2/13/56. Assign. Socony Mobil Oil Co., Inc.

Exploring Unit for Acoustical Well Logging. An acoustic logging sonde in which the transmitter and receivers are mechanically connected by a spirally-wound cable with spaced weights immersed in a fluid-filled flexible rubber jacket.

U. S. No. 2,898,088. R. L. Alder. Iss. 8/4/59. App. 3/1/54 and 2/10/58. Assign. Dresser Industries, Inc.

Earth Borehole. Logging System. A system for logging while drilling in which the logging device activates a solenoid valve that controls hydraulic fluid to space outside a rubber sleeve through which the drilling fluid flows to set up a pressure surge that is detected at the surface.

U. S. No. 2,898,414. B. A. Peters. Iss. 8/4/59. App. 7/3/58. Assign. Jersey Production Research Co.

Apparatus for Insulating High Voltage Leads through Ends of Connected Components. A separable connector plug for running high voltage leads between separable units of a neutron logging sonde arranged so that when the units are brought together the male part of the plug opens a valve to allow sulphur hexafluoride gas from one unit to flush air from the plug chamber and final tightening of the connector effects a complete seal.

U. S. No. 2,899,633. O. R. Smith and C. E. Reesby. Iss. 8/11/59. App. 4/5/56. Assign. Welex, Inc.

Well Logging Device. An electrode pad for a well-logging sonde in which the pad is made to conform to the borehole wall by means of an arm at its upper end and an arm at its lower end with the arms urged outward by separate springs.

U. S. No. 2,900,517. J. C. Allen and R. C. Reynolds. Iss. 8/18/59. App. 12/8/55. Assign. Texaco Inc.

Productivity Well Logging. A device for detecting and identifying fluids entering a well and having on its side an elongated cage containing loose radioactive spheres of different densities and with a radioactivity detector at the top and at the bottom of the cage so that the number of spheres floating and sinking in the fluid can be determined.

U. S. No. 2,901,685. R. L. Alder. Iss. 8/25/59. App. 10/18/54. Assign. Dresser Industries, Inc.

Apparatus for Earth Borehole Investigating and Signaling. An electrical encoding system for converting an electrical quantity into coded pulses for pressure signalling in a logging operation conducted during drilling.

(See also patents 2,898,084 and 2,898,575 listed under Seismic Prospecting)

MISCELLANEOUS

U. S. No. 2,890,345. G. Muffly. Iss. 6/9/59. App. 3/6/56. Assign. Gulf Research & Development Co.

Method of Converting Magnetic Recordings to Visual Images by Use of Radioactive Magnetic Materials. A method of producing visible copies for a magnetic record by causing a magnetic material that is also radioactive to adhere to the magnetized portions of the record and then exposing a photosensitive medium to the record.

U. S. No. 2,890,449. S. B. Pickles, S. H. M. Dodington, and G. Stavis. Iss. 6/9/59. App. 12/2/53. Assign. International Telephone and Telegraph Corp.

Radio Navigation System. A position location system in which the mobile craft transmits coded interrogation pulses to a beacon whose reply includes reference signals that are amplitude modulated with a bearing indicating signal.

U. S. No. 2,890,451. J. E. Hawkins. Iss. 6/9/59. App. 5/4/55. Assign. Seismograph Service Corp.

Radio Location System. A phase-comparison type of radio location system using three spaced transmitting stations and in which reference signals are developed at one of the stations by heterodyning signals from the other two stations and the beat frequency is used to modulate the carrier.

U. S. No. 2,891,108. J. H. Wiens. Iss. 6/16/59. App. 8/3/53. Assign. Thirty percent to Reed C. Lawlor.

Aerial Reconnaissance System. An aerial mapping system using television transmission from the survey plane to a base station and in which the scanned area is divided into strips each of which is linearly scanned transverse to the plane's motion and the images reproduced transverse to motion of a photosensitive film.

U. S. No. 2,891,812. L. W. Gourley. Iss. 6/23/59. App. 3/12/56.

Soil Sampling Device. A tubular soil sample cutter having two telescoping tubes whose lower ends are cut off at an angle and have sharp lower cutting edges.

U. S. No. 2,892,154. K. R. Johnson. Iss. 6/23/59. App. 8/1/56. Assign. Minneapolis-Honeywell Regulator Co.

Measuring Instrument. A galvanometer unit for a multielement oscillograph having an outer tube with a lens and an inner tube containing the suspended coil with connections from a pair of ring contacts to the coil.

U. S. No. 2,894,201. R. G. Piety. Iss. 7/7/59. App. 8/27/54. Assign. Phillips Petroleum Co.

Core Logging Method and Apparatus. A system for electrically logging a drill core in which the core is placed in a grounded trough and contacted by three semicylindrical electrodes so as to pass a current transversely through the core, the outer electrodes serving as guard electrodes for the middle measuring electrode.

U. S. No. 2,896,442. F. H. Bailly. Iss. 7/28/59. App. 7/2/56.

Mineralogical Analysis. A differential thermal analysis method in which a series of samples are simultaneously heated and the differential thermal effect between pairs of samples observed so as to register differences in thermal activity from one sample to the sample from an adjacent location.

U. S. No. 2,897,443. L. I. Mendelsohn and H. T. Faus. Iss. 7/28/59. App. 11/1/55. Assign. General Electric Co.

Moving Magnet Oscillograph. A high-frequency oscillograph having a diametrically magnetized

cylindrical rotor between the poles of a signal-energized magnet and with the moving magnet mechanically connected to a recording stylus and to a vane in a fluid damping system.

U. S. No. 2,899,558. D. R. Lewis. Iss. 8/11/59. App. 1/22/57. Assign. Shell Development Co.

Method of Characterizing Solid Materials and Method of Geophysical Exploration. A method of geophysical exploration in which the pattern of thermoluminescence of rock sections or core samples is photographed and compared with photographs taken in white light to determine the intensity and location of thermoluminescent spots.

SELECTED LIST OF U. S. PATENTS ISSUED DURING JUNE, JULY, AND AUGUST OF 1959

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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, p. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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REVIEWS

REVIEWS COMMITTEE

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Introduction to Geophysics, Benjamin F. Howell, Jr., McGraw-Hill Book Company, Inc., New York 1959, 399 pp., $9.00

Introduction to Geophysics is a book that has been needed for some time. As can be expected, Dr. Howell emphasizes the phases of geophysics in which he has been most active, i.e., earthquake seismology and the associated earth structure. The scope of the book includes other geophysical phenomena as related to both the static and dynamic structure of the earth.

I am personally very happy with this book and will use it as a text in my second semester sophomore geophysics course. Much of the math is above the comprehension of the average student who will take this course, and yet it is not sufficiently complete for an advanced course. A tremendous amount of detailed information has been included, occasionally being encyclopedic in style.

I can recommend this book especially to the petroleum geophysicists and geologists; since I think they will find much information pertaining particularly to nonpetroleum geophysics, which will be of benefit and general interest.

H. M. ZENOR
University of Tulsa
Tulsa, Oklahoma

The Study of Rocks in Thin Section, W. W. Moorehouse, Harper and Brothers, New York, 1959, 514 pp., $8.00.

This latest volume in Harper's Geoscience Series is called by its author "essentially a laboratory manual." Its purpose is to provide "in a single volume a brief review of the methods of optical mineralogy, descriptions of the rock-forming minerals encountered in the more common rocks, identification tables to assist in the identification of these minerals, and descriptions of the common rock types." The book is well written and arranged as a laboratory manual to aid students in the description of rocks. Amongst its good features are a group of fine illustrations covering practically all rock types and the use of a group of commercially available rock samples as part of the illustration material. The book is hardly adequate for a practicing geologist. Due to its scope any one group of rocks is lightly treated. This applies particularly to the sedimentary rocks. And finally very few references are given from which more detailed information regarding special rock types could be found.

CHARLES PENDEXTER
Jersey Production Research Company
Tulsa, Oklahoma

Physical Geography, Fourth Edition, Philip Lake, Cambridge University Press, New York, 1959, 483 pp., $4.00.

This volume is the fourth edition of a rather comprehensive text-book of physical geography. The subject matter is not of direct interest for the geophysicist. However, the book makes a good

general reference volume, at the Junior College level, on the processes acting on the earth's surface.

The book is divided into three sections dealing respectively with the atmosphere, the ocean and the land. The first section discusses atmospheric phenomena such as pressure, temperature, moisture and circulation. The section ends with a chapter on the weather. The second section on the ocean brings out information of general interest in relation to relief of the oceans, salinity, temperature and density of sea water, and deposits on the ocean floor. Waves, tides and ocean circulation are also treated. The third section discusses very briefly the rocks and structures of the earth crust, just enough to provide the background necessary to understand the effects of the processes acting upon the land. Following this brief introduction, the section deals with land forms and their relation to ocean currents, weathering, streams, snow and ice, wind volcanoes, etc.

The three last chapters are new additions to the fourth edition of the book. The physiographical effects of storms are emphasized with examples of recent storms in England, showing how effectively physical processes are speeded up at such times. The other two chapters attempt to relate the physical and biological aspects of geography. One deals with soils and the link they made between the study of land forms and ecology; the other describes marine life in relation to its physical environment.

ROBERTO SARMIENTO
Jersey Production Research Company
Tulsa, Oklahoma

The Geochemistry of Rare and Dispersed Chemical Elements in Soils, Second Edition, A. P. Vinogradov, Consultants Bureau, Inc., New York, 1959, 209 pp., $9.50.

This book is a survey type publication listing a large amount of analytical data on trace elements in soils of the USSR. The trace element contents of the various soil types are then related both to the content of this element normally found in various types of rocks and also to the contents found in soils of other countries, particularly the United States.

In addition to a very brief introduction to the chemistry of the elements, in Chapter 3, the author discusses possible reasons for unusually high or low amounts of most of the elements where they are treated separately in the text. There are also brief references to the influence of various trace elements on plants and animal life.

The authors have included a lengthy bibliography of over 500 references which is valuable to those interested in the work on the worldwide occurrence and distribution of these rare and dispersed elements.

In summary, this book is written for a very limited group of readers. It cannot be recommended for reading of the geologist, in general, but it would be a valuable reference book for those specifically interested in the soil sciences and the biological importance of trace elements derived from soils.

R. D. MCIVER
Jersey Production Research Company
Tulsa, Oklahoma

The Mechanics of Faulting with Special Reference to the Fault-Plane Work (A Symposium), Edited by John D. Hodgson, Publications of the Dominion Observatory, Ottawa, Vol. 20, 1959, 160 pp., $3.00.

This volume of 160 pages represents the proceedings of a symposium on earthquake fault plane work which was held during the meeting of the International Union of Geodesy and Geophysics in Toronto in 1957. It contains papers by authors of many nations such as Russia, Japan, Eire, Indonesia, Canada and the United States, and thus represents a review of the latest advances attained in many lands.

The sequence of papers is arranged in such a fashion that the mechanism of faulting is treated first. Then follow those contributions which deal with the seismological fault plane method. (The latter consists in an evaluation of the records from seismological stations with a view on the determination of the orientation of the hypothetical fault which is supposed to have been active during the the occurrence of an earthquake.) Finally, there are papers dealing with the interpretation of the results.

Many of the papers are reviews of earlier publications by the individual authors. The present volume thus provides a key to references concerning fault plane work that are scattered widely over the world's seismological literature.

Turning now to the individual papers we note that the first group of papers is concerned with the general mechanism of faulting. Thus, the volume starts with a theoretical discussion of the motion at the source of an earthquake by Byerly and Stauder in which various models of faulting are discussed in relation to the seismic waves expected therefrom. This is followed by a brief note by Ingram on possible statistical means of separating compressions from dilatations in the execution of fault plane solutions based on seismograms. The mechanism of faulting is further discussed in a paper by Dix in which the model of a lubricated crack is analysed. This is followed by a paper by Press which discusses the elastic wave radiation in an ultrasonic model of a fault. The pattern of shear wave radiation turns out to be quite different from what had generally been predicted in theoretical studies.

The next group of papers summarizes results from fault plane studies. The first paper in this connection is a review by Keilis-Borok of the Russian work; it is mostly a review of a lengthy treatise in Russian which the Soviet delegation distributed during the Toronto meetings. Several hundred fault plane solutions of earthquakes are contained therein which represents by far the greatest number that has been obtained by any single group. Many of these solutions are reproduced in pictorial form in the present paper. Following this paper, the volume includes an offset-reproduction of a paper by Honda on the mechanism of earthquakes which has already been reviewed in an earlier issue of this journal. It gives a summary of the Japanese work on fault plane studies. The last paper in the present group is a summary by Ritsema of his work on Indonesian earthquakes.

The final group of papers, concerning the interpretation of fault plane studies in the light of tectonics, starts with a discussion by Hodgson of the null vector as a guide to regional tectonic patterns. In the latter paper, its author draws pictures of proposed correlations between null "vectors" (meant is the direction of zero motion in a fault plane) and supposed tectonic features without, however, proceeding to give an explanation of same. The correlations are claimed to have a world-wide significance although all fault plane solutions provided by Russian and Japanese authors are excluded from the analysis (as being "unreliable"). Since the latter constitute the vast majority of solutions available in some of the areas analysed, the significance of the results deduced would appear as somewhat doubtful. Hodgson's paper is followed by a report by McIntyre and Christie in which an attempt is made to deduce the kinematics of faulting from seismic data. The next paper is by Benioff presenting evidence that the whole Pacific Ocean basin is rotating counter-clockwise with regard to its margin. The final paper, by St. Amand, lists field evidence in support of this idea.

All in all, the volume under discussion presents a good summary of the present status of earthquake fault plane investigations. Anybody desiring to become informed about the latest advances in this field will not want to miss it.

A. E. SCHEIDEGGER
Imperial Oil Limited
Calgary, Canada

Symposium on Geophysics in Kansas, Bulletin 137, edited by William W. Hambleton, State Geologica Survey of Kansas, Lawrence, 1959, 375 pp.

In this symposium, twenty-five papers by thirty-one authors discuss and evaluate geophysical exploration in Kansas. The very encouraging foreword by Wallace E. Pratt credits geophysics with its structural applications and the stimulation to re-examine conventional concepts. This keynotes the entire volume since all papers are concerned with the coordination of geophysical measurements and geological concepts. Hence, the introduction is aptly presented in two papers: one on the geological framework and the other on exploration geophysics. The remaining twenty-three papers ascend the geological column from the basement to the surface.

Three gravity papers and four aeromagnetic papers generally agree that the regional anomalies are largely due to intrabasement causes, that the gravity and magnetic pictures complement each other, and that some structural information may be inferred from detailed surveys.

The reflection seismic method is thoroughly discussed in eleven papers: one on the Hutchinson salt, one on various seismic interpretation techniques, two on seismic problems on the Pratt anticline and the Central Kansas Uplift, and seven case histories of oil pools in various tectonic provinces. The primary seismic problem is that of converting travel times to depths of penetration to show structural attitudes. Erroneous interpretations are largely due to lateral variations in velocity which are caused by lateral variations in evaporites and carbonates. Some readers will disagree with the solution of these problems, especially in the very small quantities which the seismograph is expected to measure. However, the authors demonstrate oil discoveries or a reduced dry hole frequency in their favor.

Five papers discuss and evaluate various geophysical techniques used in engineering and mining. They make the volume inclusive of all known geophysical methods and complete the picture from the basement to the surface.

The editor is certainly to be congratulated for soliciting and obtaining such interesting papers containing somewhat confidential data and illustrations. This symposium does commemorate the International Geophysical Year with an excellent source book of all phases of geophysical work in Kansas.

F. A. Roberts
The Carter Oil Company
Oklahoma City, Oklahoma

Propagation of the Cylindrical Explosive Sound in the Medium Consisting of Two Semi-infinite Liquids, Hirokichi Honda and Kinya Emura, *The Science Reports of the Tohoku University, Geophysics*, Vol. 10, 1958, pp. 59–70.

A two dimensional problem is considered consisting of a line source situated in the low velocity region of a medium formed by two semi-infinite liquids. An exact transient solution is developed for the displacement field, the form of the time dependence of the pressure source apparently being the derivative of an impulse. Some numerical evaluations are then performed, particular interest being centered on the nature of the refracted arrival. It is interesting to note that an approximate solution to the problem is also developed, the relevant integrals being evaluated by the saddle point method. Unfortunately the time behavior of the source is chosen to be somewhat different from that employed in the exact solution. Nevertheless a comparison of the computations clearly indicates that the approximate technique predicts the correct type of behavior in the neighborhood of the arrival times of the direct and reflected waves. The approximation is considerably poorer in the vicinity of the refracted wave arrival time. This phenomenon has now been observed by several independent investigators. It appears that the approximations generally employed will yield a reasonably accurate solution for a refracted disturbance in only a very narrow time interval around the arrival time of that disturbance. Much detailed work is necessary in order to extend this time interval in which good accuracy exists.

J. W. C. Sherwood
California Research Corporation
La Habra, California

On Converted Waves by a Narrow Canal on the Surface of a Semi-infinite Elastic Medium, Ziro Suzuki and Akira Ishigaki, *The Science Reports of the Tohoku University, Geophysics*, Vol. 10, 1958, pp. 71–79.

The experimental results of a two dimensional model study are given. A transmitter and a receiver formed of barium titanate are located at a straight edge of a thin bakelite plate in a direct simulation of a problem initially studied theoretically by H. Lamb. An incision is made at and normal to the edge of the plate at a location between the transmitting and receiving transducers. A conventional model seismology survey is then performed and time distance plots constructed for the significant events. This process is repeated for a range of incision lengths. The results give clear evidence of P wave to Rayleigh wave conversion and vice versa at the incision. Some evidence is also indicative of P to P wave conversion. This latter phenomenon, and also Rayleigh to P wave transformation,

would presumably have been more clearly portrayed by locating the source and receiver on the same side of the incision.

The experimental determinations of Suzuki and Ishigaki are compatible with the original observations of Tatel and Tuve. It would now be instructive to tie in the experimental observations with a simple theoretical investigation. A study of the effect of typical seismic shot and receiver arrays on these converted waves is also indicated.

J. W. C. SHERWOOD
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La Habra, California

Die Karte der Bouguer-Isanomalen 1:1,000,000 von Westdeutschland (Map of Bouguer anomaly contours at the scale 1:1,000,000 for West Germany), Karl Gerke, *Mitteilung Nr. 25 des Instituts für angewandte Geodäsie*, 1957 12 pp. This is also Heft Nr. 46, Teil I of Reihe B, Angewandte Geodäsie, of the Deutsche Ge ᵡ ätische Kommission bei der Bayerischen Akademie der Wissenschaften.

Bermerkungen zur Karte der Schwerestörungen des deutschen Alpenvorlandes (Notes on the gravity anomaly map of the German Alpine foreland), Hans Cloos and Albrecht Hahn (with contributions from Albert Schleusener), *Geologisches Jahrbuch*, Vol. 72, 1957, p. 503–528.

These two publications are briefly noted here for the benefit of those who may be interested in maps of gravity data for Germany. For the map in the first publication listed, the contour interval is five milligals. In the second reference listed, the map is presented in two halves, plates 28 and 28a. The scale is 1:300,000 and the contour interval one or two milligals. The sources of the data and the methods of reduction used are described in the textual portions of the publications. In the second one, attention is also given to the interpretation of the gravity data, with consideration moreover of magnetic vertical intensity data.

THOMAS A. ELKINS
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Pittsburgh, Pennsylvania

PUBLICATIONS RECEIVED

BOOKS

Methods and Case Histories in Mining Geophysics, Canadian Institute of Mining and Metallurgy, Mercury Press Co., Montreal, Quebec, 1959, 359 pp., (No Price).

Magnetic Results from Mawson Antarctica, by W. H. Oldham, Bureau of Mineral Resources, Geology and Geophysics, Commonwealth of Australia, Report No. 39, (No Price).

Canadian Geophysical Bulletin, Vol. 2, National Research Council of Canada, Ottawa, Dec. 1958, (No Price).

Contemporary Geodesy, Geophysical Monograph No. 4, Pub. by Amer. Geoph. Union, $5.50.

Our Mineral Resources, by Chas. M. Riley, John Wiley and Sons Inc., $6.95.

Dana's Manual of Mineralogy, Revised by Cornelius S. Hurlbut, Jr., John Wiley and Sons, Inc., $11.50.

PERIODICALS

American Journal of Science, v. 257, n. 7 & 8 (1959)
Annales de Geophysique, v. 15, n. 3 (1959)
Annali di Geofisica, v. 12, n. 2 (October, 1959)
Bollettino Di Geofisica, v. 1, n. 1 & 2 (July & October, 1959)
Bulletin of The Earthquake Research Institute, v. 37, part 2 (June, 1959)
Bulletin of the Research Council of Israel, v. G8, n. 1 (May, 1959)

Bulletin of the Seismological Society of America, v. 49, n. 3 & 4 (July & October, 1959)
Bulletin of the Seismological Station, n. 27, 28, 29 & 30 (1953, 1954, 1955 & 1956)
Chronique de l'Union Géodésique et Géophysique Internationale, n. 21, 22 & 23 (May, July & September, 1959)
Deutsches Hydrographisches Institut Jahrbuch, v. 13 (1958), v. 10, n. 2502 (1959)
Deutsche Hydrographische Zeitschrift, v. 12, n. 1 & 2 (1959)
Economic Geology, v. 54, n. 4, 5 & 6 (1959)
The Egyptian Journal of Geology, v. 2, n. 2 (1958)
Erdöl Und Kohle, v. 12, n. 6, 7, 8 & 9 (June, July, August & September 1959)
Freiberger Forschungehefte, v. C61, C70, C66, C65 & C63 (1959)
Geofizikai Közlemények, v. 8, n. 1–2 (1959)
Geofysiske Publikasjoner, v. 20, n. 12 & 13 (March & June 1959), v. 21, n. 2 (Aug. 1959)
Geophysical Abstracts, v. 177 (April & June 1959)
Geophysical Digest, v. 6, n. 4 (October 1958)
Geophysical Notes, v. 12, n. 1 (1959)
Geophysical Prospecting, v. 7, n. 2 (June 1959)
Gerlands Beiträge Zur Geophysik, v. 68, n. 3 & 4 (1959)
Institute of Petroleum Review, v. 13, n. 151, 152 & 153 (July, August & September 1959)
The Journal of Earth Sciences Nagoya University, v. 6, n. 2 (Dec. 1958), v. 7, n. 1 (March 1959)
Journal of Geomagnetism and Geoloectricity, v. 10, n. 3 & 4 (1959)
Journal of Geophysical Research, v. 64, n. 7, 8, 9 & 10 (July, August, September & October 1959)
Journal of the Institute of Petroleum, v. 45, n. 427 (July, 1959)
Journal of Petroleum Technology, v. 11, n. 7, 8, 9 & 10 (July, August, September & October 1959)
Journal of Technology, v. 3, n. 2 (December 1958)
Mining Engineering, v. 11, n. 7, 8, 9 & 10 (July, August, September & October 1959)
Nachrichten aus dem Karten und Vermessungswesen, v. 1, n. 10 & 11, v. 2, n. 3 & 4 (1959)
Physics Today, v. 12, n. 6 & 8 (June & August 1959)
Proceedings of the Cambridge Philosophical Society, v. 55, n. 3 (July, 1959)
Quaderni di geofisica applicata, v. 18, n. 19 (1957–58)
Quarterly Journal of the Geological Society of London, v. 114, part 4, n. 456 (June, 1959), v. 115, part 1, n. 457 (October, 1959)
The Review of Scientific Instruments, v. 30, n. 6 (June 1959)
American Association for the Advancement of Science, v. 129, n. 3346–3360 (1959)
The Science Reports of the Hohoku University, 5th Series, Geophysics, v. 11 (August 1959) v. 11, n. 1 (September 1959)
Tellus, v. 11, n. 2 (May, 1959)
Transactions American Geophysical Union, v. 40, n. 2 & 3 (1959)
Transactions & Proceedings of the Geological Society of Africa, v. 61 (1958)
Zeitschrift für Geophysik, v. 25, n. 1 (1959)

ABSTRACTS FROM *GEOPHYSICAL PROSPECTING*

Official Journal of the European Association of Exploration Geophysicists*
Volume VII, Number 2, June, 1959

Time Variations of the Calibration of the Worden Gravity-Meter

G. INGHILLERI

Precision calibration tests carried out with a Worden gravimeter in environment conditions as varied as possible have led to the following conclusions. The secular variation curve of the calibration shows that the secular relative variation has been very appreciable in the first year of life of the instrument, precisely of 1.3×10^{-3} in 13 months, while it has been practically zero in the second year. This must be ascribed to the fact that at the beginning of the operations the gravity-meter had just arrived from the factory with its measuring body renewed.

On the other side the effect of 24°C. of temperature, difference between two series of determinations, reveals itself in a variation of 0.0022 of the value of the calibration, so that it can be established that the variation of the calibration is 1% for each 10°C. of temperature variation.

Variation of the Worden Gravimeter Small Dial Scale Factor with Time

S. SAXOV

A series of repeat observations during a period of 5 years reveal a variation with time of the Worden gravimeter No. 142 small dial spring system. A possible change in the gravity difference concerned is ruled out. It is shown that the small dial scale factor has diminished by about 0.25% within the last two years against about 0.5% four to five years ago. The ratio of L.D. to S.D. has been analysed and the results obtained show confirmation of the change in the small dial system and prove a consistency in the large dial system.

The Plus-Minus Method of Interpreting Seismic Refraction Sections

J. G. HAGEDOORN

The elastic impulse from an explosion is propagated through the earth as an expanding shell bounded by the wavefront. This wavefront and its motion are a physical reality while rays or trajectories are much less sharply defined and cannot actually be observed because the wavelengths involved in seismic processes are too long. This means that the visualization and the interpretation of seismic processes can be carried out in a more satisfactory, simple and comprehensible way with wavefronts than with rays.

H. R. Thornburgh (1930) introduced the very lucid and simple method of interpreting seismic refraction sections, using Huygen's principle to construct wavefronts from two symmetrical shotpoints by working back from their observed arrival times at the surface. The depths are found first with only a knowledge of the velocities down to the refractor and after that the velocities in the refractor can be determined.

The pattern of the two wavefronts at equal time intervals, obtained when carrying out Thornburgh's construction, leads to the very simple, approximative "Plus-Minus" method. The additions of the travel times from two symmetrical shotpoints to each geophone give the relative depths and their subtractions give the velocities of the refractor. The method extrapolates exact quantities from the refractor boundary up to the surface by the "Plus"- and "Minus" lines. This extrapolation introduces errors that can, more or less, be corrected for. A number of hypothetical cases are presented to give an insight into the applicability and reliability of the "Plus-Minus" method. Its main applications are for fairly shallow refraction investigations and for determining weathering corrections for refraction and reflection work.

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A Three-Component Magnetometer for Small Drill-Holes and Its Use in Ore Prospecting

A. E. LEVANTO

A 3-component flux gate magnetometer has been built for use in 1¼ inch drill-holes. It has an accuracy of 1 mgs. It requires 2–3 men to operate it and they can take measurements in up to 3 100 metre holes in one day. The instrument has definitely proved its worth in describing the "general" geology of an ore-body, and it is now used on a routine basis.

Design Considerations of a Bore-Hole Gravimeter

D. W. N. DOLBEAR

Due weight must be given to three factors (1) its purpose, (2) the limitations imposed by nature, industry and environment, (3) the effect of errors in auxiliary measurements. Together the last two factors give an estimate of the accuracy which can be achieved. If this is sufficient for the instrument to fulfil its purpose design and construction can proceed. If it is not, a detailed survey of the last two factors is necessary in order to estimate the research effort that will be required when directed into the most effective channels. If the project is considered worth the effort it can proceed. These factors are discussed in relation to a bore-hole gravimeter. It is shown that the purpose will be served only if the accuracy is comparable with the best surface gravimeters. Bore-hole versions of some surface instruments are considered and it is concluded that none is suitable without considerable modifications. A successful bore-hole gravimeter is likely to be a completely new instrument.

Application of the Continuous Velocity Log to Anisotropy Measurements in Northern Sahara; Results and Consequences

PH. DUNOYER DE SEGONZAC* AND J. LAHERRERE

Anisotropy measurements were carried out in two wells 300 km apart in the Northern Sahara, in order to improve the interpretation of seismic refraction surveys.

These measurements were based on the shortening of experimental oblique travel-times with respect to theoretical travel-times computed by disregarding anisotropy. A perfect knowledge of the velocity distribution is required in order to eliminate all influence of refraction; therefore a continuous velocity log is indispensable.

The results in the two wells are in agreement, and show that anisotropy is essentially a function of lithology. The following values were obtained:

Sandstones, sands	$k=1$
Salt	$k=1{,}00$ to $1{,}05$
Limestone	$k=1{,}08$ to $1{,}12$
Anhydrite	$k=1{,}15$ to $1{,}20$

Consequences pertaining to seismic refraction are as follows:

—Depths computed without anisotropy are too small by 8% to 9%, i.e. about 300 meters.

—The error on offsets reaches 70%.

—Depth computations carried out by assigning anisotropy factors at the sight of lithology gave very satisfactory results.

—High velocity, highly anisotropic formations such as anhydrite play a very important part in the propagation of refracted waves and in interpretation.

Consequences pertaining to seismic reflection are as follows:

—Velocity profiles yield velocities closer to horizontal velocities than to vertical velocities.

—Depth and migration computations are significantly influenced by high velocity, highly anisotropic formations such as anhydrite.

Well Velocity Determinations in the English Trias, Permian and Carboniferous

S. M. WYROBEK

To obtain inferences useful in predicting the overburden velocities, a statistical study of velocity data was undertaken on 46 well velocity surveys confined mainly to Eastern England. Five formations were particularly studied: Keuper, Bunter, Permian, Coal Measures and Millstone Grit. Their interval velocities plotted against the mean depth of the interval below the surface supplied five equations of the form $V=k\cdot H^{1/n}$, which cover the range of depth explored down to 7,000 ft. Comparison of these results shows that the interval velocities increase with depth and in the Keuper and Permian attain a maximum value nearly twice that in the remaining three formations. The interval velocities of these formations are confined within a relatively narrow band of 9,000–12,000 ft/sec and the formations cannot be distinguished satisfactorily by their interval velocities alone. More practical results were obtained considering the relation between the vertical time and depth to the top of the Permian, Coal Measures, Millstone Grit and Carboniferous Limestone. For each of these a linear relation $T=k\cdot H+T_0$, was obtained from which the vertical time T can be predicted from the known depth with a probable error of ± 4 millisecs.

Problems and Results with Refraction Seismics in Boreholes

W. HOLSTE

Recently, quite good determinations of interfaces have been made by means of seismic well surveys. These were carried out for various oil companies in Northwest Germany, especially on salt-domes, and in Southern Germany, and in the area of the Upper Rhine Valley. It was the purpose to determine the configuration and position of salt-flanks and important planes of stratification in the neighbourhood of deep wells, and thus to reduce the risk of expensive wells.

For the delineation of the boundary surfaces the method described by GARDNER in "Geophysics 1949" was applied.

The problems arising and the results obtained are discussed in connection with some interesting examples. From them we see, above all, that a knowledge as precise as possible of the seismic velocities of all media involved in the measurement is very important. A good idea of the general stratification in the area of deep wells seismically surveyed will make possible a rational and adequate planning of the survey program and will facilitate the interpretation.

ABSTRACTS FROM *GEOPHYSICAL PROSPECTING*
Volume VII, Number 3, September, 1959

On Elastic Surface Waves at a Cylindrical Hole in an Infinite Solid

G. STILKE

Solutions for the propagation of elastic waves at the surface of a cylindrical hole of infinite length are derived from the wave equation for a perfectly elastic and isotropic medium. It is found that the phase and group velocities depend on the ratio between the wave length and the circumference of the cylindrical hole. These surface waves can be classified into different orders. They differ in the calculated dispersion curves, in the range of possible wave lengths (cut-off-frequencies), and in the amplitude proportion of the components of the displacement vector. For very short wave lengths these waves converge to normal Rayleigh waves.

These results are used to explain some of the multiple onsets and disturbances on seismograms, obtained in practical seismic investigations in the mines of Siegerland. The conformity of theoretical and practical results is limited, because the idealised suppositions on which the computation is based, such as perfect elasticity, homogeneous and isotropic medium, and circular cross-section of the mine gallery are met only approximately in practice.

Results of Underground-Seismic Reflection Investigations in the Siderite District of the Siegerland

G. SCHMIDT

The iron ores of the Siegerland district are found in lodes occurring in schists of Lower Devonian age. These lodes, normally dipping almost perpendicularly, could be traced only by seismic reflection measurements underground, up to distances of approximately 500 m. The geophones were attached to the walls of the galleries. The frequencies of the recorded longitudinal and transverse waves ranged from 200 to 500 c.p.s. By this method a new siderite lode was discovered.

Results of Surface Reflection Seismic Measurements in the Siderite District of the Siegerland

R. REICHENBACH AND G. SCHMIDT

The iron ores of the Siegerland district are found in lodes occurring in schists of Lower Devonian age. In the course of the geophysical exploration for these ores, an attempt was also made to clarify the structure and the tectonics of the substratum of the sedimentary rock formations by seismic reflection measurements from the surface. Reflections were recorded in great numbers from layers of Silurian and Devonian age. The form of the folding of the strata derived therefrom corresponds well with that deduced from geological investigations. Beyond that, correlatable reflections were recorded from horizons down to a depth of nearly 25,000 m. It turned out that the iron ore lodes known from the mine workings occur almost vertically above those places where greater dislocations appear in the deepest substratum, and which geologically could be interpreted as fracture zones. The results so far obtained seem to be indicative of the fact that the tectonics of the deepest substratum and the occurrence of ore deposits are related to each other.

Geophysical Exploration in Mining by Induced Polarization

F. ŠUMI

The present paper deals with various causes giving rise to potential differences caused by induced polarization. In order to obtain the induced polarization effect of ore bodies it is necessary to determine the effect of the barren rock and subtract it from the total observed effect.

Results of field measurements carried out by this method in the mercury mine of Idrija, as well as those in the lead-zinc mine of Mežica and the Kankberg ore district are in good agreement with the geological data. A theoretically calculated profile is compared with an actual field profile.

Introduction to the Interpretation of Resistivity Measurements for Complicated Structural Conditions

L. ALFANO

A study is made of the possibility of calculating electric potentials, and therefore of interpreting apparent resistivity measurements, when the ground presents structural conditions more complicated than plane, parallel stratification.

For this work a schematic type of structure has been chosen, in which the discontinuity planes for electric resistivity are both parallel and perpendicular to the level of the ground.

The problem has been examined in its general aspect, and then some criteria for the numerical calculation have been indicated.

Some calculated examples are presented, relevant to vertical electric soundings accomplished by conventional technique, for particular types of structure.

LETTERS TO THE EDITOR

GEOPHYSICS' SILVER ANNIVERSARY*

We congratulate you and all the previous editors of GEOPHYSICS on a consistently fine journal. Your plans for the Silver Anniversary issue are further evidence of excellent editorial judgment.

In these days, when so many exciting things are being done in geophysics, all of us have the problem of finding time to read a fraction of the papers we want to read. Authors and editors therefore have a duty to perform: to prepare papers so that the readers can understand them as quickly as possible. One of the best discussions of how to achieve this objective is "Preparation of a Paper" by Lawrence Y. Faust, GEOPHYSICS, v. 23, p. 945–952 (1958).

J. A. PEOPLES, JR.
Editor of *Journal of Geophysical Research*

* Received by the Editor October 22, 1959.

LETTER TO PRESIDENT McCOLLUM*

I appreciated your prompt notification of the SEG election results concerning the editor's race. Thanks very much, too, for the very kind letter which followed the wire.

The SEG is fortunate to have a man of Dr. Steenland's background and ability as its next editor. My very best wishes go with him as he assumes his official duties and responsibilities.

As for me, there are no regrets. The honor of having been in the race for editor overshadows the defeat. The confidence in me which the nominating committee expressed by virtue of its action is a continuing source of encouragement for me to try to be as good a geophysicist as possible.

Each year the influence and prestige of our technical journal has become more evident. GEOPHYSICS is being quoted more frequently in the journals of related fields now than ever before. The degree of sophistication of our papers has increased markedly. Let us hope these signs of growth continue for many years. It is natural that our studies should advance deeper into theory and farther out into unorthodox techniques. Yet, with all this, it is important to remember that oil-finding and mineral-finding is our business. Down-to-earth papers dealing with operational aspects of our industry thus continue to have a most important and vital function. The point of this pargraph is simply to pay tribute to those who have helped make the SEG and particularly GEOPHYSICS, what it is today and to express the hope that future years will see continued development of our society into a truly outstanding professional organization.

As one views the expanding role of earth sciences in human thought to date, the future of geophysics, in its broader and long-term sense, looks practically unlimited.

E. J. STULKEN

* Received by the Editor August 11, 1959.

GEOPHYSICAL ABSTRACTS*

I have read with interest the exchange between MM. Chastenet de Gery and Naudy and Mr. Hutchison (GEOPHYSICS, v. 24, p. 604–605) concerning the difficulties in scanning current geophysical literature.

Those of us who labor to produce *Geophysical Abstracts*, a quarterly publication of the U. S. Geological Survey designed for the express purpose of alleviating some of those difficulties, are repeatedly disheartened to find that numbers of geophysicists are still unaware of, or do not avail themselves of, this service. *Geophysical Abstracts* are issued as Bulletins of the Geological Survey, and may be purchased, as single copies or by subscription, from the Superintendent of Documents, Govern-

* Received by the Editor October 22, 1959.

ment Printing Office, Washington 25, D. C. Single copies cost 40 cents, subscriptions $1.75 a year or ($2.25 foreign). Prices quoted are effective January, 1960.

For this ridiculously small sum we offer abstracts of more than 1,400 papers a year; periodicals and books received in the Geological Survey library, Library of Congress, and other sources are regularly searched for material dealing with both basic and applied geophysics. In spite of limitations of money, staff, and availability of some journals, abstracts from any important journal, such as *Geophysical Prospecting*, are usually in print three to six months after the journal is received.

An abstract of the paper by Nepomniachik, of which MM. Chastenet de Gery and Naudy and Mr. Hutchison were all unaware, appeared in *Geophysical Abstracts* no. 149, April–June, 1952 which was distributed in September, 1952. An abstract of the paper by MM. Chastenet de Gery and Naudy appeared in no. 172, January–March, 1958, which was published in June, 1958.

In closing, may I remind readers of the fact that abstracts are not intended to substitute for the full paper, merely to draw attention to it and give as good an idea of the contents as can be conveyed in a few words.

(Mrs.) Dorothy B. Vitaliano
Editor, Geophysical Abstracts
U.S.G.S., Washington, D. C.

CONTRIBUTORS

J. S. BRADLEY

J. S. BRADLEY attended the Colorado School of Mines, receiving a degree of geological engineer in 1948, and the University of Washington, receiving a Ph.D. in geology in 1952. He worked with Humble's geologic research section from 1950 to 1954 and at the Institute of Marine Science of the University of Texas from 1954 to 1956. He joined Atlantic Refining Company's research and development department in 1956 as supervisor of the chemical exploration group. He is presently supervisor of the geologic group of the exploration section.

JOHN M. CRAWFORD is Director of Exploration Research in Continental Oil Company's Development and Research Department. Born in Madison, Kansas, he received his A.B. degree from Phillips University in 1932 and his M.S. degree from the University of Oklahoma in 1934 with a major in Physics. He joined Continental in 1934 as an assistant operator on a seismic crew. He later held positions of development engineer, control geophysicist, and superintendent of gravity exploration. In 1950, he transferred to the Development and Research Department where he organized the Geophysical Research Division. He is a member of the SEG, American Geophysical Union, and the American Association of Petroleum Geologists.

JOHN M. CRAWFORD

WILLIAM E. N. DOTY

WILLIAM E. N. DOTY received the B.S. degree in Electrical Engineering from Oklahoma State University in 1948. Upon graduation, he was employed by the Geophysical Department of Continental Oil Company. He transferred to the Geophysical Research Division of the Development and research Department in 1950, where he is presently working as a Supervising Research Geophysicist.

R. J. GRAEBNER

R. J. GRAEBNER is area geophysicist for U. S. and Canadian operations of Geophysical Service Inc. He obtained his B.S. degree in Engineering Physics from the University of Colorado in 1948 and his M.S. degree in Physics from the same university in 1954. Mr. Graebner joined GSI in 1949 as a computer. In 1953 he was appointed seismologist, and was made senior research seismologist in 1955. Mr. Graebner is a member of the SEG and the Dallas Geophysical Society.

HELEN GRAY

HELEN GRAY graduated from Texas Women's University in 1945 with a B.A. in Mathematics. She later took work in geology at Dallas College, S.M.U. She worked for National Geophysical Company in 1945–1946 as a junior computer on a field crew. In 1948, she went to work for Magnolia Petroleum Company as an apprentice draftsman and is presently a senior seismic computer. She is a member of the Society of Exploration Geophysicists and the Dallas Geophysical Society.

J. C. HARRISON was born in Co Durham, England, on May 20, 1929. He was educated at the Perse School, Cambridge and at Cambridge University, where he read Natural Sciences. After specializing in physics for Part II of the Tripos in 1950, he joined the Department of Geodesy and Geophysics at Cambridge as a research student and obtained his Ph.D. in 1953.

Dr. Harrison came to the Institute of Geophysics of the University of California in 1953 but returned to England early in 1955 to serve for two years in the Royal Navy as an Instructor Lieutenant. He returned to the Institute of Geophysics in 1957.

J. C. HARRISON

MILFORD R. LEE received the Ph.D. degree in Physics from Kansas State College in 1953. Since that time, he has been employed by Continental Oil Company, and at present, is a Research Group Leader in the Exploration Research Division.

MILFORD R. LEE

J. P. LINDSEY

J. P. LINDSEY was born in Wichita Falls, Texas in 1926 After attending Midwestern University in 1943, he served in the Navy for two years and then entered Oklahoma State University where he received the degree of B.S. in Electrical Engineering in 1949. Upon graduation, he joined the Texas Electric Service Company as a distribution engineer. In 1950 he became associated with the Civil Aeronautics Administration in Oklahoma City as a Radio Engineer. During this time he completed the requirements for the M.S. degree in Electrical Engineering at Oklahoma State University and was granted the degree in 1954. In 1953 he joined the Research Division of Phillips Petroleum Company where he is presently engaged in Geophysical research.

Mr. Lindsey is a member of the Society of Exploration Geophysicists and the Geophysical Society of Tulsa.

HAROLD M. MOONEY

HAROLD M. MOONEY graduated from Harvard College in 1943 with B.S. in physics. Following World War II, he worked for a short time with Geophysical Explorations, Ltd., in Quebec, and then entered California Institute of Technology in 1946. He received Ph.D. in geophysics, majoring in earthquake seismology, in 1950. Since 1950, he has been Assistant Professor and Associate Professor of Geophysics at the University of Minnesota. Summer employment has included work for several geophysical companies, oil companies, and government agencies. During part of 1959, he was visiting lecturer at the Institute of Geophysics, Federal Institute of Technology, Zurich, Switzerland.

T. F. MOORE attended Juniata College, Huntingdon' Pennsylvania, 1940–42. He received his B.S. degree in chemistry in 1944 from Southern Methodist University and worked with Atlantic until he entered the armed forces. He served with the Manhattan Corps of Engineers at Oak Ridge from 1944 to 1946, developing methods of purifying and recovering uranium 235. In 1946 he returned to Atlantic, where he worked in the reservoir mechanics group. In 1948 he went to Johns Hopkins University, receiving his M.A. degree in 1949 and Ph.D. in 1950. He returned as a group leader in the research department in 1950 to engage in studies of fluid flow in porous media, chemical well logging and exploration, and currently, drilling and production stimulation techniques.

T. F. MOORE

Dr. G. R. PICKETT received a B.A. degree in mathematics and an M.S. degree in physics, both from the University of Oklahoma. Since receiving a D.Sc. degree in geophysical engineering from Colorado School of Mines in 1955, he has been employed by Shell Development Company. He has been engaged in applied research on well-log interpretation, with emphasis on reservoir evaluation through use of borehole acoustic logs.

G. R. PICKETT

FRANK PRESS

FRANK PRESS born December 4, 1924, Brooklyn, New York. He received his B.S. from the College of the City of New York 1944, M.A. from Columbia University 1946, Ph.D. from Columbia University 1949.

Research Staff Division of Government Aided Research, Columbia University 1946–1949; Research Associate in Geology, Columbia University 1948–49; Instructor in Geology 1949–51; Assistant Professor of Geology 1951–52; Associate Professor of Geology, 1952–55; Professor of Geophysics, California Institute of Technology since August 1955, and Director, Seismological Laboratory July 1957 to present; Expert in Seismology UNESCO Foreign Technical Assistance Mission to Israel 1953; International Geophysical Year Glaciology and Seismology Panel 1955, Committee on Polar Research 1957; Consultant U. S. Navy (1956), USGS (1957), Department of State (1958), Department of Defense (1958).

Press's main contributions have been in the fields of experimental and theoretical seismology. His experimental work includes identification of the *Lg* phase, analysis of mantle Rayleigh waves, studies of the *T*-Phase and microseisms, field discovery of air-coupled surface waves, long period seismograph development, seismic refraction and reflection measurements at sea and model seismology. His theoretical work includes dispersion of Rayleigh waves (including the effect of water for oceanic paths), theory of air-coupled flexural and Rayleigh waves, and propagation of elastic waves in layered media.

Member or Fellow, Honors: Tremaine Scholar 1943; Honors in Physics C.C.N.Y. 1944; University Fellow Columbia University 1948; Alfred P. Sloan Fellow 1957, 1958; Columbia University Medal for Excellence 1959; Phi Beta Kappa; Sigma Xi; American Association for Advancement of Science (Member of Council); American Physical Society; American Geophysical Union; Geological Society of America; Society of Exploration Geophysicists; Seismological Society of America; New York Academy of Sciences; National Academy of Sciences; Co-editor Arden House Microseism Symposium Volume (National Research Council); Co-editor Physics and Chemistry of the Earth; Seismology Editor Trans. AGU 1956, 57; Secretary Seismological Society of America 1957, 58.

Geophysical Fields: Earthquake and Seismology; Exploration Geophysics; Submarine Geology; Theory of Elastic Wave Propagation; Crustal and Mantle Structure.

MOTOAKI SATO

Motoaki Sato graduated from the University of Tokyo with a B.S. degree in geology in 1953, and received his M.S. degree in geology from the same institution in 1955. He was awarded a Fulbright/Smith-Mundt scholarship from the U. S. Government for two years from 1955 to 1957 to study at the University of Minnesota, from which he received a Ph.D. degree in geology in 1959. He was a staff member of the Department of Geophysics of the same University from 1956 to 1958, working on a research project for the U. S. Atomic Energy Commission. He is presently associated with Harvard University as a post-doctoral fellow in geophysics, and is working on geochemical problems related to ore deposits. He is a member of the Geochemical Society, the Mineralogical Society of America, the Geological Society of Japan, and the Society of Mining Geologists of Japan.

MANIK TALWANI received his B.Sc. (Hons.) degree in 1951 and M.Sc. degree in 1953, both in physics, from Delhi University, India. Worked with Geofysisk Malmleting, the Norwegian Government ore prospecting institute, in Trondheim, Norway, in 1953–1954. Entered Columbia University in 1954 and has been associated with Lamont Geological Observatory since then. He has held the Higgins, Lydig and University fellowships. Received his Ph.D. in geophysics in 1959. Member of Society of Exploration Geophysicists, American Geophysical Union, Geological Society of America, Seismological Society of America and the Society of Sigma Xi.

MANIK TALWANI

B. B. WEATHERBY

BENJAMIN B. WEATHERBY received his A.B. degree from Haverford College, 1921; A.M., 1922. He was instructor of physics at Lafayette College, 1921–23; assistant professor of physics University of Toledo, 1923–24; associate professor 1924–25. He was chief of field party, Geophysical Research Corporation, 1926–27. He was instructor of physics at the University of Pennsylvania from 1927–29, where he received his Ph.D. degree.

Dr. Weatherby was division chief, Geophysical Research Corporation 1929–31, Vice-President 1931–33, and President since 1933. He has been a director of the Amerada Petroleum Corporation since 1935, Vice-President since 1938, Senior Vice-President since 1955. He was Chairman of the War Efforts Advisory Committee, Society of Exploration Geophysicists, World War II; consultant to the Office of Scientific Research and Development; chairman Manpower Sub-committee District II Production Commission, Petroleum Industry War Council; co-chairman Hall of Science, International Petroleum Exposition 1940, chairman, 1948.

He is a member of the American Physical Society, American Institute of Mining and Metallurgical Engineers, American Association of Petroleum Geologists (associate editor 1932), Society of Exploration Geophysicists (editor, 1934, President, 1935), American Geophysical Union, American Petroleum Institute, Sigma Xi, Phi Beta Kappa.

Dr. Weatherby has received five patents for geophysical oil prospecting.

J. E. WHITE

Dr. J. E. WHITE received a B.A. degree in 1940 and an M.A. degree in 1946, both from the University of Texas. He received a Ph.D. from the Massachusetts Institute of Technology in 1949. The major subject in each case was physics. From 1941–1945, Dr. White worked on underwater sound problems at the Massachusetts Institute of Technology, serving as director of the MIT Underwater Sound Laboratory during the last year of this period. He then spent one year in guided missiles research at the Defense Research Laboratory in Austin before returning to MIT for graduate work. From 1949 to 1955 he had charge of a group engaged in geophysics research at the Field Research Laboratories of the Magnolia Petroleum Company. In 1955 he joined The Ohio Oil Company as Physics Research Supervisor at the Denver Research Center. Dr. White is a member of the Acoustical Society of America, Society of Exploration Geophysicists, American Physical Society, Seismological Society of America, and Society of Petroleum Engineers of AIME.

WILLIAM C. WOOLLEY

WILLIAM C. WOOLLEY graduated from the University of California at Los Angeles with a B.A. in Physics in 1934 and took a year of graduate work in physics at U.C.L.A. He joined the Rieber Laboratory in the fall of 1935 and later transferred to their Houston, Texas office. He joined Magnolia Petroleum Company in the fall of 1938 as a geophysical helper on seismic crews and advanced to jr. computer in 1941 when he was transferred to the Dallas office as Geophysicist where he has worked on seismic interpretation, velocity control and special problems. He is a member of the Society of Exploration Geophysicists, currently serving on the Publicity and Public Information Committee. He is a member of the Dallas Geological Society and a member and officer of the Dallas Geophysical Society.

DR. PAUL C. WUENSCHEL received a degree of Geological Engineer from Colorado School of Mines in 1944. He did graduate work in geophysics at Columbia University and received a Ph.D. degree in 1955. He worked with the Lamont Geophysics Group in Gravity and Marine Geophysics from 1946 to 1952. Since 1955, he has been associated with the Gulf Research and Development Co. as a research geophysicist working on elastic wave propagation problems. Dr. Wuenschel is a member of Sigma Xi, Seismological Society of America, American Geophysical Union, and Acoustical Society of America.

PAUL C. WUENSCHEL

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows: W. T. Born, v. 24, p. 1154; H. F. Dunlap, v. 22, p. 468; Maurice Ewing, v. 23, p. 1052; Lucien J. B. LaCoste v. 24, p. 397; Albert W. Musgrave, v. 23, p. 179; L. L. Nettleton, v. 22, p. 474, also p. 33 this issue; Carl H. Savit, v. 23, p. 182.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN NOVEMBER 1960

EXECUTIVE COMMITTEE

President: T. O. HALL, General Geophysical Company, Houston, Texas
First Vice-President: FRANK SEARCY, Continental Oil Company, Ponca City, Oklahoma
Vice-President: DEAN WALLING, Western Geophysical Co. of America, Los Angeles, California
Secretary-Treasurer: PHIL P. GABY, Consultant, Jackson, Mississippi
Editor: NELSON C. STEENLAND, Gravity Meter Exploration Company, Houston 27, Texas
Past President: E. V. MCCOLLUM, E. V. McCollum & Company, Tulsa, Oklahoma

Nominations
T. O. HALL, *Chairman*
E. V. MCCOLLUM
O. C. CLIFFORD, JR.
(To be appointed)

Honors and Awards
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R. C. DUNLAP, JR. ('62)
ROY F. BENNETT ('63)

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CURTIS H. JOHNSON, *Chairman*
(Committee to be appointed)

American Geological Institute Directors
(To be appointed)

AGI Glossary
(To be appointed)

AGI Committee on Licensing
(To be appointed)

AAAS Council Representative
CHARLES W. OLIPHANT

Distinguished Lectures
J. W. THOMAS ('60), *Chairman*
A. J. HINTZE ('60)
A. W. MUSGRAVE ('61)
GEORGE P. WOOLLARD ('61)

Safety
KENNETH A. WEBB, *Chairman*
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E. L. WELLS
HERBERT FERBER
G. M. HINTZ

Mining Geophysics
STANLEY H. WARD, *Chairman*
(Committee to be appointed)

Membership
JACKSON YOUNG, *Chairman*
(Committee to be appointed)

Publicity
(To be appointed)

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FRANK BROWN ('60), *Chairman*
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WM. J. ROBINSON ('62)

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Index of Wells
V. U. GAITHER, *Chairman*

Case Histories
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Geophysical Activity
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C. N. HURRY
DR. KUMIJI IIDA
BART W. SORGE
L. R. TUCKER
J. A. PEOPLES

Radio Facilities
(To be appointed)

Research
J. P. WOODS, *Chairman*
(Committee to be appointed)

LOCAL SECTIONS

Ark-La-Tex Geophysical Society (6), Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

Canadian Society of Exploration Geophysicists (9), Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
H. J. Kidder, *pres.*
M. B. Dobrin, *v-pres.*
P. J. Savage, *secty-treas.*, Nance Exploration Co., Condon Bldg., Calgary, Alta.

Casper Geophysical Society (11), Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

Coastal Bend Geophysical Society (24), Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

Cochabamba Geophysical Society (23), Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
Paul D. Balbin, *pres.*
Roger Heggblom, *v-pres.*
Frank Ellsworth, *secty-treas.*, Western Geophysical Co., Casilla 1495, Cochabamba, Bolivia.

Dallas Geophysical Society (4), Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

Denver Geophysical Society (8)
John C. Hollister, *pres.*
Arthur W. Black, *v.-pres.*
Charles E. McMunn, *secty-treas.*

Geophysical Society of Edmonton (22), Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

Fort Worth Geophysical Society (5)
O. A. Strange, *pres.*
R. H. Dana, *v.-pres.*
U. A. Rowe, *secty.*
C. H. Thurber, *treas.*

Four Corners Geophysical Society (19), Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

Geophysical Society of Houston (2), Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

Jackson Geophysical Society (15)
Joel Macgregor, *pres.*
John Babb, *v-pres.*
Thomas Tillman, *secty-treas.*

Montana Geophysical Society (14), Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
R. E. Whitmore, *pres.*
W. H. Dawson, *1st v-pres.*
N. L. Hull, *2nd v-pres.*
T. E. Young, *secty-treas.*, Shell Oil Co., Box 2547, Billings, Mont.

New Mexico Geophysical Society (18), Roswell, N. M., chartered September 18, 1957, officers elected in May.
E. J. Medley, *pres.*
R. E. Lawson, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
H. C. Ives, *secty-treas.*, Atlantic Refg. Co., Box 6640, Roswell, N. M.

Geophysical Society of Oklahoma City (10), Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

Pacific Coast Section (3), luncheon ($2.75) Rodger Young Auditorium, Los Angeles.
F. F. Lambrecht, *pres.*
Nolan A. Webb, *v-pres. S.D.*
M. C. MacMurrough, *v-pres. N.D.*
Tom Slaven, *secty-treas.*

Permian Basin Geophysical Society (7), Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
R. A. Baile, *pres.*
J. E. Clark, *1st v-pres.*
J. W. Rogers, *2nd v-pres.*
R. E. Phipps, *treas.*
D. M. Matson, *secty.*, Midwest Oil Corp., 1500 Wilco Bldg., Midland, Texas.

Regina Geophysical Society (22)
A. C. Armstrong, *pres.*
B. F. Fulton, *v-pres.*
J. R. Muir, *secty-treas.*

Geophysical Society of South Texas
J. W. E. Edmonson, *pres.*
P. J. Rudolph, *v-pres.*
Donald W. Jones, *secty-treas.*

Southeastern Geophysical Society (13), New Orleans, La. chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($1.50), St. Charles Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

Southwest Louisiana Geophysical Society (16), Lafayette, La., chartered January 4, 1956, officers elected in December.
Neal Clayton, *pres.*
J. A. Standridge, *1st v-pres.*
C. J. Sieb, *2nd v-pres.*
J. S. Peterson, *treas.*
F. H. Hammons, *secty.*, Pan American Petroleum Corp., Box 1463 OCS, Lafayette, La.

Geophysical Society of Tulsa (1)
K. S. Cressman, *2nd v-pres.*

Utah Geophysical Society (17)
L. D. Oster, *pres.*
K. L. Cook, *1st v-pres.*
G. F. Slattery, *2nd v-pres.*
D. J. O'Halloran, *secty.-treas.*

Asociacion Venezolana de Geofisica (21)
W. J. Pfeffer, *pres.*
D. F. Warner, *1st v-pres.*
A. P. Seifert, *2nd v-pres.*
D. W. Danz, *treas.*

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado.
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois.
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology.

SEG Houston Student Section
Billie Gail Dopslauf, *secty.* 2121 Hollister, Houston, Texas

University of Toronto Geophysical Society
B. R. Krause, *secty.* 502 Gilbert Ave., Apt. 107, Toronto, Ont., Canada

University of Tulsa Student Geophysical Society
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma.
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
El Paso, Texas

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced.

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah.
Meetings: Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced.

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas.

SOCIETY AFFILIATIONS

American Association for the Advancement of Science

SEG is affiliated under Section E, Geology and Geography
1515 Massachusetts Avenue
Washington 5, D. C.
Paul E. Klopsteg, *President*
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The American Association of Petroleum Geologists

A Cooperative relationship
Box 979
Tulsa 1, Oklahoma
L. G. Weeks, *President*
A. H. Bell, *Vice-President*
H. T. Morley, *Secretary-Treasurer*
G. E. Murray, *Editor*
G. S. Buchanan, *Past President*
R. H. Dott, *Executive Director*

American Geological Institute

SEG is a charter member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
Raymond C. Moore, *President*
Ian Campbell, *Vice-President*
Paul Lyons, *Past President*
Donald H. Dow, *Secretary-Treasurer*
R. C. Stephenson, *Executive Director*

European Association of Exploration Geophysicists

Mutually affiliated
30, Carel Van Bylandtlaan
The Hague, Netherlands
J. M. Bruckshaw, *President*
V. Baranov, *Vice-President*
B. Baars, *Secretary-Treasurer*
O. Koefoed, *Editor*
L. Solaini, *Past President*

National Research Council, Division of Earth Sciences

SEG is a member society
2101 Constitution Ave., N.W.
Washington 25, D. C.
John N. Adkins, *Chairman*
Harry H. Hess, *Past Chairman*
Edward B. Espenshade, Jr., *Chairman-Designate*
William R. Thurston, *Executive Secretary*

Petroleum Exploration Society of Libya

Mutually Affiliated
P. O. Box 900
Tripoli, Libya
Sam Frazier, *President*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Jakob Andres (A. Schleusener, Th. Krey, W. Stemmler & J. Schander)
William Moecker Baehr (W. H. Dawson, J. P. Duncan, W. E. Martin & C. T. Phillips)
Richard Carl Banister (R. A. Baile, L. B. Snedden, M. E. Trostle & C. W. Payne)
Joe Brennan, Jr.
Thomas Gaienie Bruner
John Herbert Bruce Campbell (E. J. Shimek, L. L. Nettleton, N. C. Steenland & L. Paitson)
Leo Chester Cummings, Jr. (W. M. Rust, Jr., R. R. Thompson, D. H. Gardner & F. J. Feagin)
Roland Degallier (A. deSpengler, P. Lasfargues)
Willis Wally Dungan (J. A. Lester, A. W. Musgrave, J. C. Eley & G. W. Ehlert)
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Henry Lane King (G. W. Lisle, M. P. Jones, L. H. Cobb & O. M. Holmes)
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Jack Lynn Wilson (G. W. Isensee, J. S. Page, J. A. Lester & R. M. Nugent)
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Lee Kingston Arnold

Anand Mohan Awasthi (L. D. Oster, C. H. Savit, T. L. Slaven & J. W. Peters)
Charles Lothrop Elliot (A. A. Brant, L. O. Bacon & R. J. Searls)
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Robert Dean Hilliker (I. L. Nash, S. W. Fruehling, R. F. Aldredge & N. K. Moody)
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William Wallace Kerr (J. E. MacGregor, J. R. Reese, J. H. Wallace)
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ANNOUNCEMENTS

SOVIET EXPLORATION GEOPHYSICS

The subcommittee on Russian translations presents its first list of references of Soviet books and papers of interest to exploration geophysicists. The style and arrangement are on a trial basis to be modified as experience indicates a need. Important errors can be corrected by reinsertion. Comments, suggestions, and corrections of errors will be considered carefully by the subcommittee.

Special attention is called to the following:

1. Journals are indicated by keys, with an explanation of each at the end of the list. The explanation shows the full title, transliterated and translated. Supplementary information is given for some journals, especially those in the SOV/STEP program.
2. Marginal symbols are used to facilitate rapid selection and reference. The class and field of the entry and the type of English presentation, are shown. The symbols are explained at the end of the list.
3. Sources of English discussions are shown by symbols explained at the end of the list. The information given should enable the reader to determine whether further search is desirable, and to obtain the material easily.
4. This list is intended as an index, and contains no abstract or analysis of the material cited.

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SYMBOLS AND ABBREVIATIONS

Class: I—interpretive; M—model study; P—physical properties; Q—equipment; S—field survey; T—theoretical; U—summary.

Field: a—alternating current; c—earth currents; d—radiation; e—electromagnetic; g—gravity; h—high frequency; m—magnetic; r—resistivity, or equipotential; s—seismic or elastic; t—thermal.

Type: Abs—abstract; Con—translation of table of contents, usually with additional information; Dig—digest, longer than an abstract, often sufficient for use without reference to original; Ed—editorial comment; Ref—reference or title, usually without additional information; Rev—review; Tr—translation in full, sometimes omitting translations of figures, formulas, and tables.

Abbreviations: ed—editor or editor-in-chief; mi—microfilm; no.—number; p.—page; ph—photostat; v.—volume.

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SOV-15: Referativnyy Zhurnal, Geologiya. (Abstracts Journal, geology). No longer issued by OTS. For detailed information about the item cited, consult OTS.

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X-3: Studia Geophysica et Geodaetica. Československá Akademie Věd (Geophysical and Geodetic Studies. Czechoslovakian Academy of Sciences). Praha (Prague).

X-4: Práce Geofysikálního Ústavu Československé Akademie Věd, Geofyskálni Sbornik (Papers of the Geophysical Institute of the Czechoslovakian Academy of Sciences, collected geophysical papers) Praha (Prague).

X-5: Moksliniai Pranešimai Lietuvos TSR Mokslu Akademiya, Geologijos ir Geografijos Institutas (Akademiya Nauk Litvoskoy SSR, Nauchnyye Soobshcheniya Geologicheskogo i Geografi-

cheskogo Intituta) (Scientific Reports, Academy of Sciences of the Lithuanian SSR, Geological and Geographical Institue). In Russian, Vilnius (Vilna).

X-6: Akademiya Nauk Grusinskoy SSR, Soobshcheniya (Communications of the Academy of Sciences of the Georgian SSR) Tbilisi (Tiflis).

X-7 Akademiya Nauk Gruzinskoy SSR Institut Geofiziki Trudy (Academy of Sciences of the Georgian SSR, papers of the Institute of Geophysics) Tbilisi (Tiflis).

X-8: Akademiya Nauk SSSR, Ural'skiy Filial, Trudy, nr. 30, Gorno-Geologicheskogo Instituta, geofizicheskiy sbornik (Academy of Sciences of the USSR, Ural Branch, papers of the Mining-geological Institute, collected papers, no. 30) Sverdlovsk.

X-9: Akademiya Nauk Ukrainskoy SSR, Institut Geologichnykh Nauk, Trudy, Seriya geofizicheskaya (Academy of Sciences of the Ukrainian SSR, Institute of Geological Sciences, papers, geophysical series), In Russian. Kiev.

X-10: Geologiya Nefti i Gaza (Geology of Oil and Gas), monthly, translated in two semi-monthly parts by Petroleum Geology, See PG.

X-11: Geofizikai Közlemények. A Magyar Állami Eötvös Loránd Geofizikai Intézet (Geophysical Publications. The Hungarian National Roland Eotvos Geophysical Institute) Budapest.

X-12: Moskovogo Geologicheskaya Razvedka Institut, Trudy (Transactions of the Moscow Geological Exploration Institute).

X-13: Akademiya Nauk SSSR, Institut Fiziki Zemli, Trudy (Academy of Sciences of the USSR, Institute of Physics of the Earth, papers) Moscow.

X-14 Sovetskaya Geologiya. Ministerstvo geologii i okhrany nedr. (Soviet Geology, Minister of geology and conservation of natural resources). Moscow.

X-15: Akademiya Nauk Turkmenskoy SSR, Izvestiya. (Academy of Sciences of the Turkmen SSR, Bulletin) Ashkhabad, Turkmen SSR.

X-16: Trudy Akademii Neftanoy Promyshlennosti (Papers of the Academy of the Petroleum Industry) Moscow.

X-17: Akademiya Nauk SSSR, Sovet po Seysmologii, Byulleten (Academy of Sciences of the USSR, Seismology Council, Bulletin) Moscow.

X-18: Izvestiya Akademiya Nauk SSSR, Seriya Geograficheskaya i Geofizicheskaya (News of the Academy of Sciences of the USSR, Series Geography and Geophysics). This has been replaced by SOV-10 and SOV-49.

X-19: Izvestiya Akademiya Nauk SSSR. Otdeleniye Materii i Estestvennogo Nauku) News of the Academy of Sciences of the USSR, Department of Materials and Natural Sciences).

X-20: Piroda (Weather). USSR.

X-21: Banyaszati Lapok. Hungary.

PUBLISHERS, JOURNALS, AND SOCIETIES

* Order number and price, if shown.

** For subscription rates, see GEOPHYSICS, yearbook, 1959.

AGU** American Geophysical Union, 1515 Massachusetts Avenue N.W., Washington 5, D. C.

ATS* Associated Technical Services, Inc., P.O. Box 271, East Orange, N. J.

CB* Consultants Bureau, 227 W. 17th St., New York 11, N. Y.

CCT* Consultants Custom Translations, Inc., 227 West 17th St., New York 11, N. Y.

CTT Columbia Technical Translations, 5 Vermont Avenue, White Plains, N. Y.

GA Geophysical Abstracts, U. S. Geological Survey, quarterly, 35¢ each, $1.25 a year. The first number is that of the issue, the second that identifying the abstract in the issue. Issues 164–167 are Bulletin 1048 (1956), 168–171 are Bulletin 1066 (1957), 172–175 are Bulletin 1086 (1958). In each bulletin, part A is January to March, part B is April to June, part C is July to September, part D is October to December. The index is part E, if included.

IGR** International Geology Review, 601 West 115th St., New York 25, N. Y.

LC* Photoduplication Section, Library of Congress, Washington 25, D. C.

OTS* Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.

PB—T Publication number of OTS covering SOV/STEP cards.
PG** Geologiya Nefti i Gaza (Geology of oil and Gas) Petroleum Geology, 509 South Lee St., Alexandria, Va.
SLA* Special Libraries Association Translation Center, The John Crerar Library, 86 Randolph Street, Chicago 1, Ill.
TM Translation Monthly, OTS. Superseded January 1959 by TT.
TT** Technical Translations, OTS, semi-monthly.

IRWIN ROMAN, Chairman
Subcommittee on Translation of Russian Publications

EDITOR'S SUPPLEMENTAL REPORT

As promised in the Editor's Report on pages 883–885, December 1959, this supplement completes the report of the activities of the eleventh Editor of GEOPHYSICS. The total number of pages of material in Volume XXIV, 1959 was 1,172 instead of the estimated figure of 1,132. Two items were omitted from the original report, namely, Reviews—Publications Received which totaled 39 pages for Volume XXIV and Discussions and Communications and Letters to the Editor comprising 46 pages.

This present issue completes the activities of the eleventh Editor of GEOPHYSICS. This issue contains 13 technical papers including four on Seismic Theory and Experimental Seismology, two on Gravity and Magnetic Prospecting, one on Well-Logging, two Miscellaneous Technological, one Electrical Prospecting with application to Mining Geophysics, one Instrumentation, and one Exploration Geophysics.

The pages of material in this issue are: Presidential Address 3, Technical Papers 232, Discussions and Communications 14, Reviews—Publications Received 6, Letters to the Editor 2, Patents 11, Contributors 9, Committees 1, Local Sections and Society Affiliations 2, Announcements 17, Personal Items 3, Other Non-Technical Papers 80, Calendar of Meetings 1. The total pages of material in this issue are 384.

The decision to make GEOPHYSICS a bi-monthly beginning with this issue was made with the expectation that substnatially the same number of technical papers would be published annually in five issues instead of the previous four. Under that assumption subsequent issues of GEOPHYSICS will on average contain eight to nine technical papers. In our effort to make this Silver Anniversary Issue as good as possible we have published several papers which, under normal procedures would have been reserved for later issues. We regret that to that extent we have made the task of our successor, Dr. Nelson C. Steenland, more difficult.

LAWRENCE Y. FAUST
Retiring Editor

TEACHING FELLOWSHIPS AND ASSISTANTSHIPS AVAILABLE

The Physics Department of the University of Alberta invites applications from students for graduate study in Geophysics. Research in progress includes studies of heat flow, paleomagnetism, gravity and glaciology in the Rocky Mountains, age-determination, natural electromagnetic fields, and electrical properties of the earth. Support is available in the forms of Teaching Fellowships (up to $3,600 for 12 months), Teaching Assistantships (up to $3,200 for 12 months or $2,400 for seven months), and special Fellowships worth up to $2,400 for 12 months. Applications should be sent, as soon as possible, to the Physics Department, University of Alberta, Edmonton, Alberta, Canada.

PERSONAL ITEMS

J. Cl. de Bremaecker has resigned his position with the I.R.S.A.C. in the Belgian Congo, and has been appointed assistant professor of geophysics and geology at the Rice Institute in Houston, Texas.

Dr. J. A. Erdelyi-Fazekas Norden has recently been promoted to the rank of professor of geology and petroleum geophysics in the department of geology at the University of Oklahoma.

Edmund T. Wilcox has recently resigned his position as senior computer with Western Geophysical Company and is now employed as an oceanographer with the U. S. Navy Hydrographic Office. His new home address is: 3901 Southern Avenue, S.E., Apartment 3, Washington 20, D. C.

D. F. Coolbaugh has recently returned from Burma where he was advisor in Mineral Technology to the Burmese government on a Ford Foundation project. He will continue his consulting practice with the address of Jones Road, Golden, Colorado.

M. C. Born is now chief geophysicist of Oasis Oil Company of Libya and his new address is Oasis Oil Company of Libya, P.O. Box 317, Tripoli, Libya.

Warren H. Thralls has recently retired from Arabian American Oil Company and is presently connected as vice-president with the American Geological Associates, Incorporated of Princeton, New Jersey. His mailing address is 411 Woodcrest Drive, San Antonio 9, Texas.

John R. Graham, Jr. has recently resigned from Austral Oil Company, Incorporated and has opened an office as a Consultant, specializing in exploration problems and geological-geophysical coordination.

J. Eugene Stones has recently resigned his position with The Superior Oil Company and is now employed by the Lion Oil Company, Division of Monsanto Chemical Company, and is based in their Midland office as regional staff geophysicist.

Jeff E. Miller, Jr., has recently moved his consulting office to 603 Wilson Building, Dallas 1, Texas.

Joseph Kornfeld, of Kornfeld International, Tulsa, is the author of a paper presented at the Seventeenth International Congress of Pure and Applied Chemistry in Munich August 30 through September 6, 1959. The title is "Importance of Madelung's Constant in the Calculation of Additional Coulomb Energy for Average Charge Distribution in Overlapping Ions of the Alkali Halides."

D. T. Germain-Jones has retired as Chief Geophysicist of British Petroleum Ltd., after thirty-two years with that company. He has announced his intention not to undertake further full time employment, though he intends to keep in touch with the geophysical profession in various ways. A. B. Malone succeeds Mr. Germain-Jones as Chief Geophysicist of British Petroleum Ltd.

Joseph T. Froehlich and Roy L. Lay have been appointed General Managers of the Foreign Operations Department (Eastern Hemisphere) of Texaco Inc.

Dr. Frank Press, Director of the Seismological Laboratory at California Institute of Technology, has been elected a member of the Board of United ElectroDynamics, Inc., Pasadena, Calif.

S. T. Algermissen has been appointed Assistant Professor of Geophysics at the University of Utah, Salt Lake City, Utah.

Dr. Algermissen received the B.S. degree from Missouri School of Mines in 1953, and the A.M. and Ph.D. degrees from Washington University. He was formerly associated with Sinclair Research Laboratories, Inc. in Tulsa, Oklahoma.

PHIL H. GARRISON has been appointed district exploration superintendent at Pan American Petroleum Corporation's New Orleans district.

PROFESSOR ENDERS A. ROBINSON of the Mathematics Department of the University of Wisconsin has been appointed Acting Director of the Numerical Analysis Laboratory of the University.

DR. JAMES R. WAIT, Consultant to the Director of the National Bureau of Standards' Central Radio Propagation Laboratory, has received a Gold Medal (for exceptional service) from the U. S. Department of Commerce. Dr. Wait was cited for "highly distinguished authorship in the field of radio propagation."

Academic rank promotions for five Colorado School of Mines faculty members effective Sept. 1, are as follows: GEORGE W. LEMAIRE is raised to full professor in the petroleum-refining department. Raised to the rank of associate professor are DR. PETER C. BADGLEY and DR. ROBERT M. HUTCHINSON, both in geology, and Henry A. Babcock, in civil engineering. DR. FRED E. MOORE becomes an assistant professor in geology.

DR. KENNETH L. COOK, 1778 Nevada St., Salt Lake City 8, Utah, will trade a new bound copy of Vol. 9 GEOPHYSICS (1944) ($6.00 value) for the 3 following original issues of GEOPHYSICS: Vol. IX, no. 1 (Jan., 1944); Vol. X, nos. 1 and 2 (Jan. and Apr., 1945).

FRANK GOLDSTONE, will manage Petty Limited, London office of Petty Geophysical Engineering Company according to announcement made by officials of the world wide firm. Goldstone will head the London office as Managing Director of Petty Ltd.

KARL H. KUNDERT, formerly working the general Lake Superior area as geologist and core-drill supervisor for the Atkins-Walker Company of Duluth, Minn., is now associated with the Utex Exploration Company, P.O. Box 487, Moab, Utah, and is working as geophysicist out of that office.

DR. R. J. RUNGE has been appointed to the position of Senior Research Physicist, Theoretical Geophysics, in the Geophysics Research Division at the La Habra Laboratory.

A. MARTIN EICHELBERGER, marketing executive and petroleum exploration authority, has joined Dibrell and Company, Inc., a Philadelphia-based firm of management consultants, as a participating partner and Executive Vice President in charge of Market Development.

ROBERT L. GEYER has been appointed to the position of Research Associate in the Seismic Research Section at the Pan American Petroleum Corporation Research Center, Tulsa. Since his transfer to the Research Department as a Senior Research Engineer in 1952, Mr. Geyer has worked with the field research party as an analyst and has participated in the development of techniques for the display and interpretation of seismic data.

The appointment of M. T. (TOM) STROHMEIER as general manager of the newly expanded service department of World-Wide Instruments, Inc., has been announced by TOM BEARD, president of the firm.

CHARLES E. "PREACHER" MYERS has joined Shot Point Service, Inc., as Vice President and General Manager. Shot Point Service, Inc. is engaged in contract seismograph operations in Texas, Mississippi and Florida. Its services are offered throughout the United States. The home office of the firm is at 5528 Lawndale Avenue, Houston 23, Texas.

The appointment of DONALD B. WINFREY as Assistant To The President for Petty Geophysical Engineering Company was announced here this month by the company president, Fred Lindall.

GEOPHYSICAL CONSULTING SERVICE and CRITTENDEN SEISMIC COMPANY are now associated to offer a complete record analysis and review. G. R. CRITTENDEN is owner and operator of Crittenden Seismic Company, and THOMAS C. KING is in charge of review work and interpretation. Offices are at 509 North 27th Street in Billings, Montana.

THE COMPLETION OF A THREE DIMENSIONAL SURVEY of the main body of the North and South Atlantic Ocean, the expansion of oceanography in the near future, educational policy and plans for a campaign to enlarge the Endowment Fund were among many items discussed last Thursday at the Annual Meeting of the Board of Trustees of the Woods Hole Oceanographic Institution.

Two new Trustees were elected to the body of 24 men of science and affairs—headed by Raymond Stevens, President of A. D. Little Company, who manage the affairs of the Institution. They are: HOMER H. EWING of E. I. duPont de Nemours Company and CECIL H. GREEN, Vice President Texas Instrument Incorporated, and honorary Chairman of Geophysical Service, Incorporated, Dallas, Texas.

HOWARD M. HOUSE, Owner of the House Drilling Company, has recently moved his office and operating facilities from Thermopolis, Wyoming to new headquarters at 431 N. Elk, Casper, Wyoming.

IN RECOGNITION of his engineering work "in applying the principles of geophysics to practical problems in mineral exploration," the Mining and Exploration Division of the Society of Mining Engineers of AIME has named DR. LOUIS B. SLICHTER, Director of the Institute of Geophysics at the University of California in Los Angeles, for its 1959 Daniel C. Jackling Award and to be its Jackling Lecturer.

R. M. NUGENT, "a well known figure in West Texas oil circles," has become associated with Cosden Petroleum Corporation. The announcement has been made by R. L. Tollett, president.

SANFORD D. BLATTNER, of 41 Birch Road, Darien, Conn., has been appointed chief geophysicist for Mobil Oil Company, according to William W. Clawson, manager of exploration.

Mr. Blattner was formerly senior staff geophysicist for Mobil International Oil Company. Mobil Oil and Mobil International are the domestic and foreign operating divisions of Socony Mobil Oil Company, Inc.

NEW ASSIGNMENTS for three key personnel in Seismograph Service Corporation's well logging division have been announced by JAMES M. BIRD, vice president, in charge of the Birdwell Division of SSC.

LLOYD C. FONS, former Midwest area manager for the Birdwell Division in Robinson, Ill., has been named sales manager for Birdwell with headquarters in Tulsa.

WILLIAM STURDEVANT, former Oklahoma area manager in Tulsa, will be Midwest area manager in Robinson succeeding Fons.

JOSEPH FERGUSON, who has been area manager for SSC's Continuous Velocity Logging operations, will become Mid-Continent area manager for Birdwell.

MCPHERSON-HALE CONSULTANTS LIMITED announce the opening of a consulting firm at 640-7th Ave., S. W., in the North Canadian Oil Building. They are prepared to offer geological and engineering services to the petroleum industry, with particular emphasis on oil and gas reserve evaluation and exploratory evaluation.

ELECTRODYNAMIC INSTRUMENT CORPORATION celebrated its fourth anniversary January 31 by moving into new quarters, more than doubling the space it formerly occupied at 2511 Robinhood and 2508 Tangley Rd., Houston, Texas. The company's new location on which a long term lease has been negotiated is at 1841 Old Spanish Trail. EIC has been occupying three buildings in the Village totaling 8,000 square feet of space, but the newly renovated structure on OST will provide more than 17,500 square feet, President JOE HOUGHTON stated.

FORMATION OF A FRENCH COMPANY to operate the Geograph in Europe and the French Union was announced jointly in Houston and Paris by the Robert H. Ray Geophysical Companies and Compagnie Generale de Geophysique of France.

The new company will be known as GEOGRAFRANCE with headquarters in Paris. CHARLES L. ROBINSON of Houston will serve as technical director in the Paris office.

CALENDAR OF MEETINGS

1960

February

14–18 AIME Annual Meeting, Hotel Statler and Hotel McAlpin, New York City.

22–24 Instrument Society of America, Houston, Texas.

March

21–24 IRE National Convention, New York City.

April

3–5 SEG 13th Annual Midwestern Exploration Meeting, Captain Shreve and Washington-Youree Hotels, Shreveport, La.

25–28 AAPG-SEPM Annual Meeting, Atlantic City, New Jersey.

27–30 A.G.U. Annual Meeting, Washington, D. C.

May

2–3 Society of Petroleum Engineers, AIME Wichita Falls, Texas.

October

2–5 Society of Petroleum Engineers of AIME, Fall Meeting, Denver, Colorado.

19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.

November

7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston, Texas.

10–12 G. S. A. Annual Meeting, Denver, Colorado.

14–16 API, Chicago, Illinois.

1961

February

19–23 AIME Annual Meeting, St. Louis, Missouri.

March

20–23 IRE National Convention, New York City.

April

24–27 AAPG-SEPM Annual Meeting, Denver, Colorado.

October

25–27 Gulf Coast Association of Geological Societies, San Antonio, Texas.

November

5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver, Colorado.

10–12 GSA Annual Meeting, Denver, Colorado.

13–15 API, Chicago, Illinois.

1962

March

26–29 AAPG-SEPM Annual Meeting, San Francisco, California.

26–29 IRE National Convention, New York City.

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta.

Oct. 31–Nov. 3 Gulf Coast Ass'n of Geological Societies, New Orleans, La.

1963

October

21–24 Society of Exploration Geophysicists, 33rd Annual International Meeting, New Orleans, La.

November

13–16 Gulf Coast Ass'n of Geological Societies, Hot Springs. Ark.

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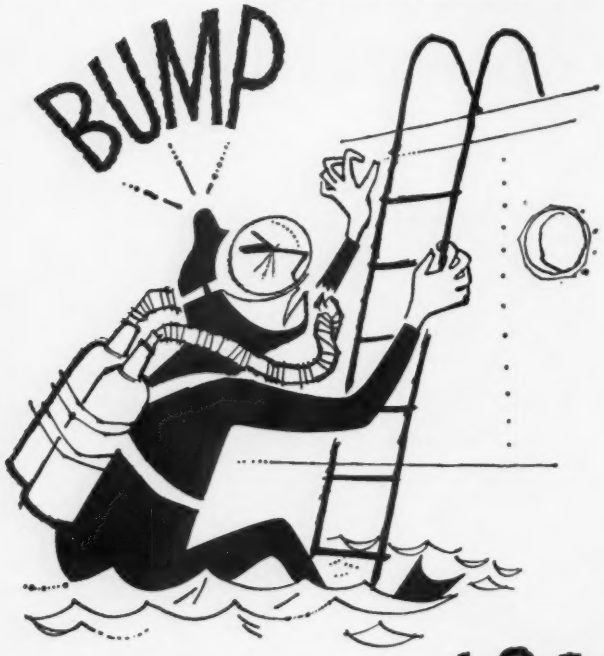

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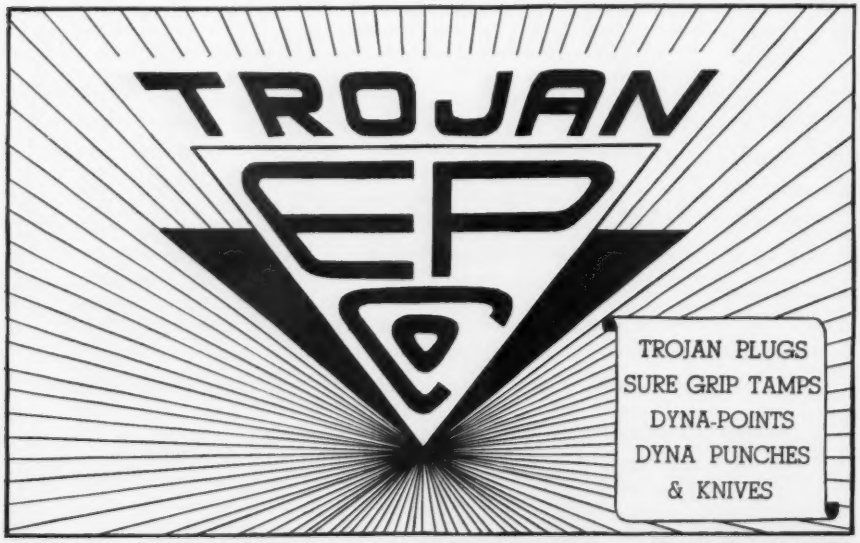

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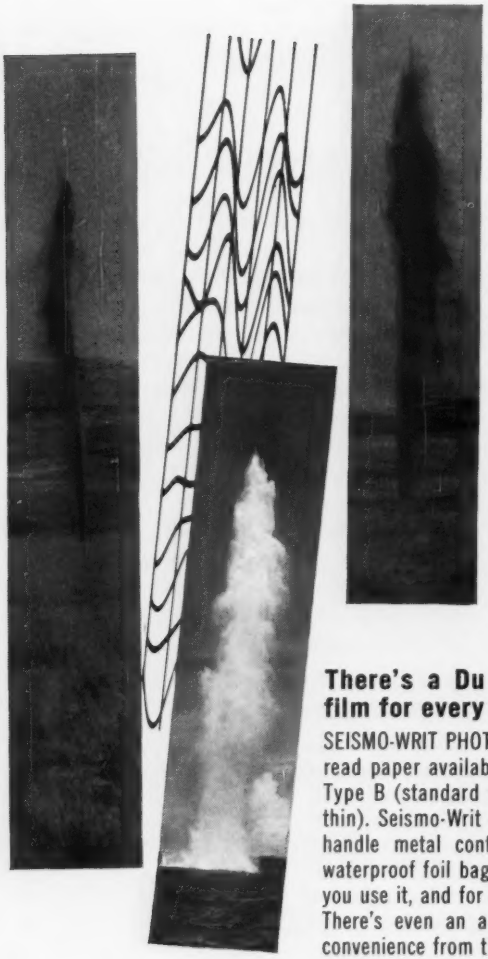

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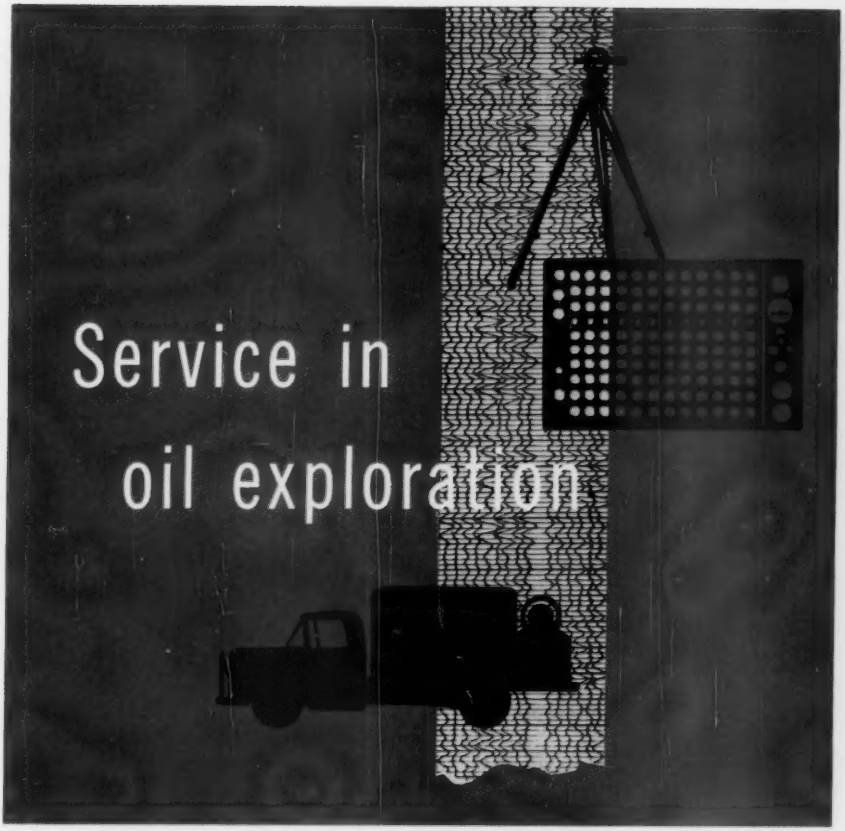

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(Continued from page 10)

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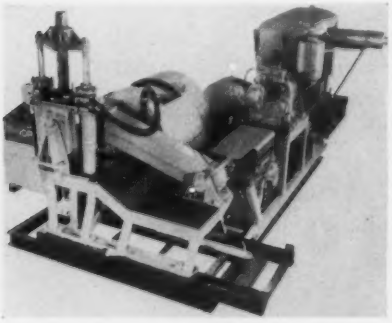

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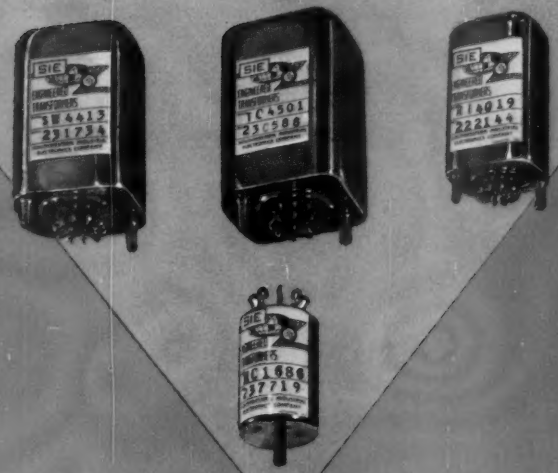

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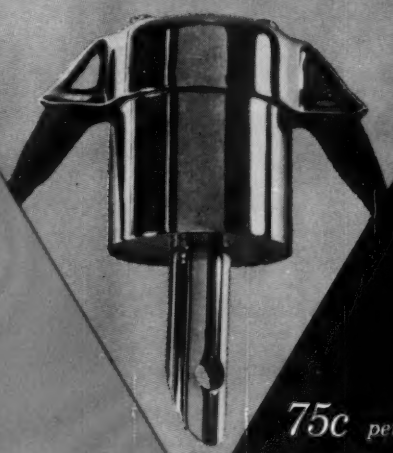

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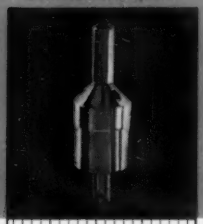

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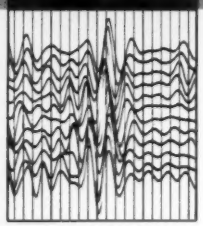

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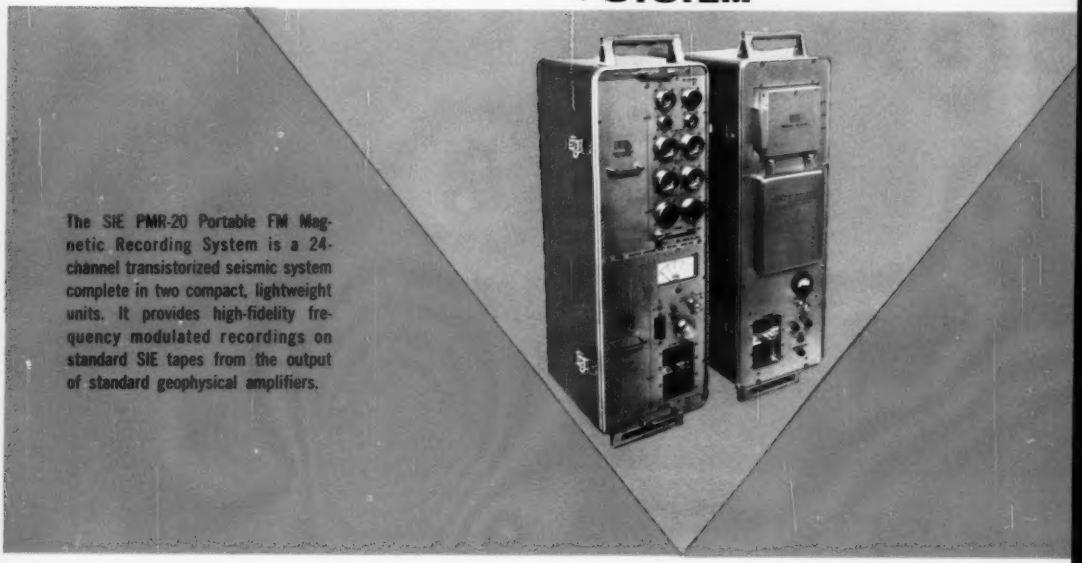

The SIE PMR-20 Portable FM Magnetic Recording System is a 24-channel transistorized seismic system complete in two compact, lightweight units. It provides high-fidelity frequency modulated recordings on standard SIE tapes from the output of standard geophysical amplifiers.

The MR-20 transport houses the recording drum, drive system and recording heads. The modulators, demodulators, and auxiliary electronics are in the MU-20 Master Unit. Each unit contains its own transistorized power supply. In addition to the 24 seismic channels, time-break, up-hole, noise cancelling and 100 cps timing reference channels are also included. Recording and playback modulation levels are read directly from a convenient front panel meter. All record-playback switching functions are accomplished from a single front-panel switch. Movable or fixed heads can be supplied as desired. Provisions are incorporated to play back tapes through seismic amplifiers or directly through

PMR-20 FM recording provides exceptionally high signal-to-noise ratio and wide frequency response — assuring maximum reproduction fidelity comparable to no other recording method. FM also eliminates the effects of tape imperfections and irregularities. In the PMR-20, all the low noise level, low distortion, high timing accuracy characteristics of the field-proven MR-4 system are combined with additional features to produce a portable, low power drain, lightweight system of outstanding field dependability and simplicity.

CONDENSED SPECIFICATIONS

Channels: 24 geophysical
4 auxiliary (Time break, up-hole, 100 cps and noise cancelling)

Frequency response: 1 cps to 300 cps within 1 db; 3 db down at 500 cps

Signal-to-noise ratio: 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

Harmonic distortion: Less than 1%

Crossfeed: Below noise level of recording system

Relative timing accuracy: ± 0.25ms.

Power requirement:

	Standby	Operating
Record	2 amp.	7 amp.
Playback	1.5 amp.	6.5 amp.

12 volts D.C.

Dimensions: MR-20 Recorder—8¼"W x 24½"H x 15"D
MU-20 Master Unit—8¼"W x 24½"H x 10½"D

Weight: MR-20 Recorder—60 lbs.
MU-20 Master Unit—45 lbs.

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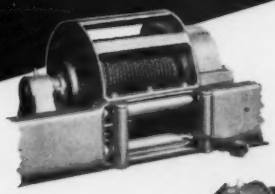

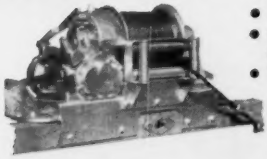

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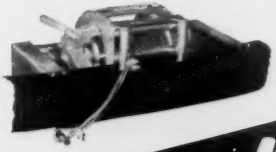

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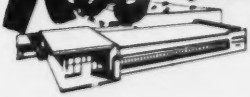

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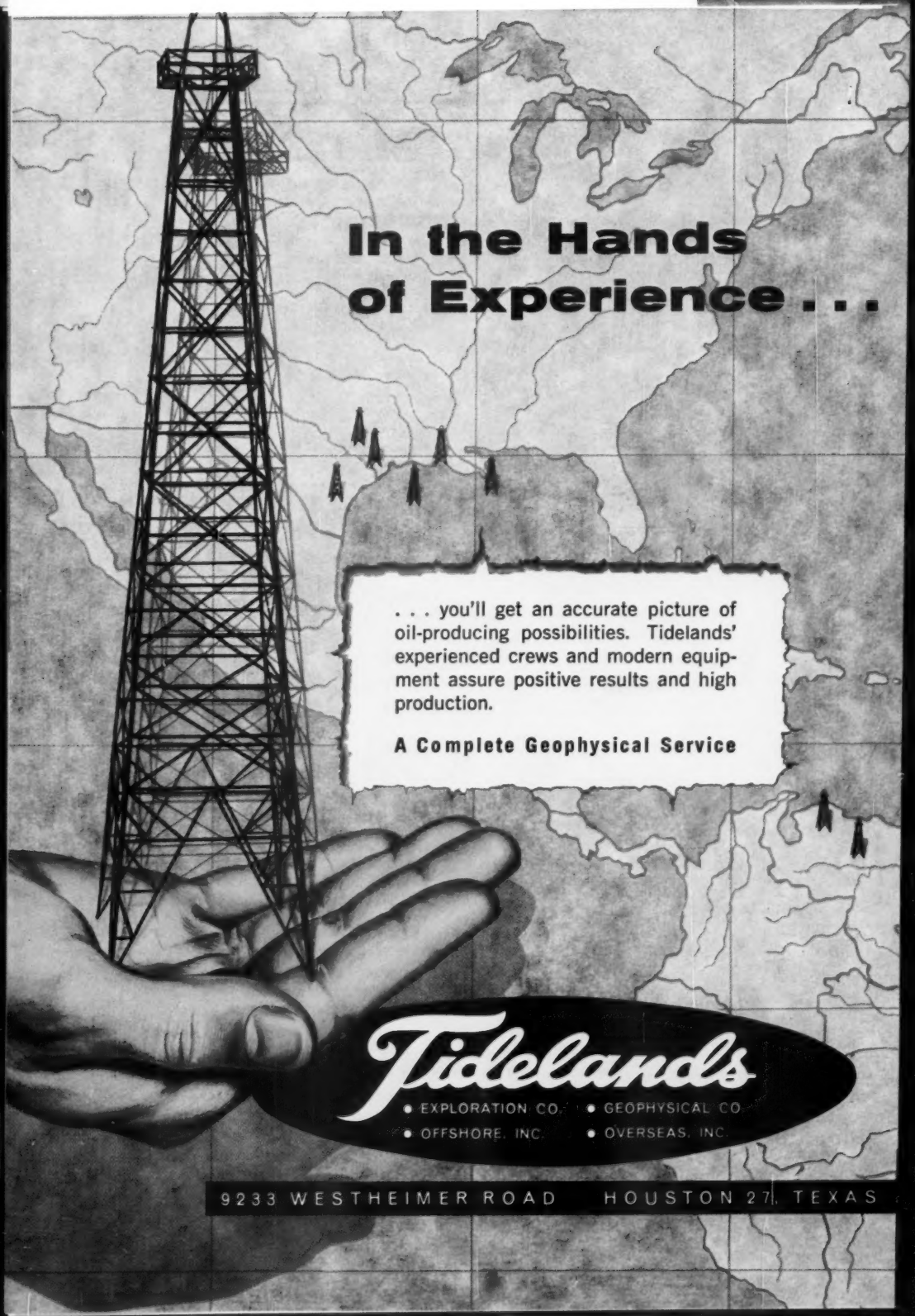
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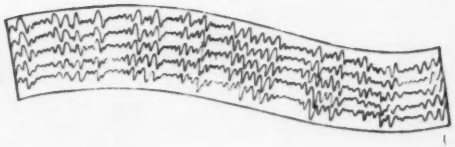

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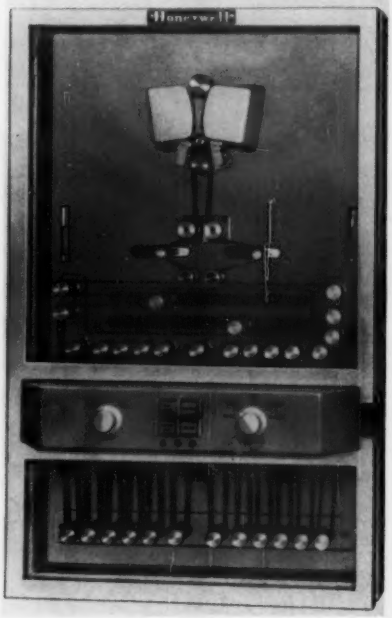
(Continued from page 33)

and powered by self-contained dry cell batteries. This extremely compact instrument weighs 17 lbs., and is packaged in a 16 × 9× 7¾ inch aluminum carrying case. **Electrodynamic Instrument Corporation, 2508 Tangley Road, Houston 5, Texas.**

TAPE HANDLERS

Three new continuous-loop transports are being made available by the Beltsville, Md., division of Minneapolis-Honeywell Regulator Company for handling magnetic tape lengths up to 35, 80 and 100 feet.



Designed for detailed analysis programs, such as those in conjunction with analog computers and with wave analyzers to examine the full frequency spectrum recorded over varying reel time periods, the loop mechanisms have isolated tape path under the multitrack record and playback heads for high precision low-flutter performance.

Tape widths up to two inches can be readily changed. Other features include up to nine tape speeds, dual tension sensors, slide mounting, and integral power supply.

The transport, designated Series 3190, has a full view door with safety interlock. All controls are located on the door at convenient working level..

A tape loop adapter for Honeywell's Series 3170 transports, of which the 3190 series is an extension, is being offered. It accommodates tape loops from 2½ to 15 feet.

For information write to: **Minneapolis-Honeywell Regulator Company, 10721 Hanna St., Beltsville, Md.**

GRAVITY-MAGNETICS BULLETIN

A new three-color, eight-page bulletin describing the use of gravity and magnetics in petroleum exploration has been prepared by Geophysical Service Inc. and is available to persons interested in exploration.

The bulletin, GM 59-1, is entitled, "GRAVITY-MAGNETICS . . . what they *can* and *can't* do for the explorationist."

Specific examples of gravity-magnetics work and information on the key variables which must be considered in any gravity-magnetics program are discussed.

The bulletin can be obtained by writing: The Marketing Department, **Geophysical Service Inc., Box 35084, Airlawn Station, Dallas 35, Texas.**

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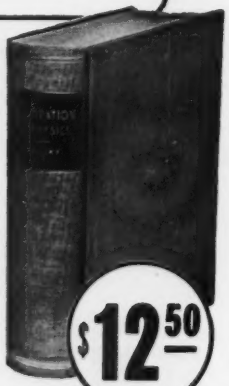

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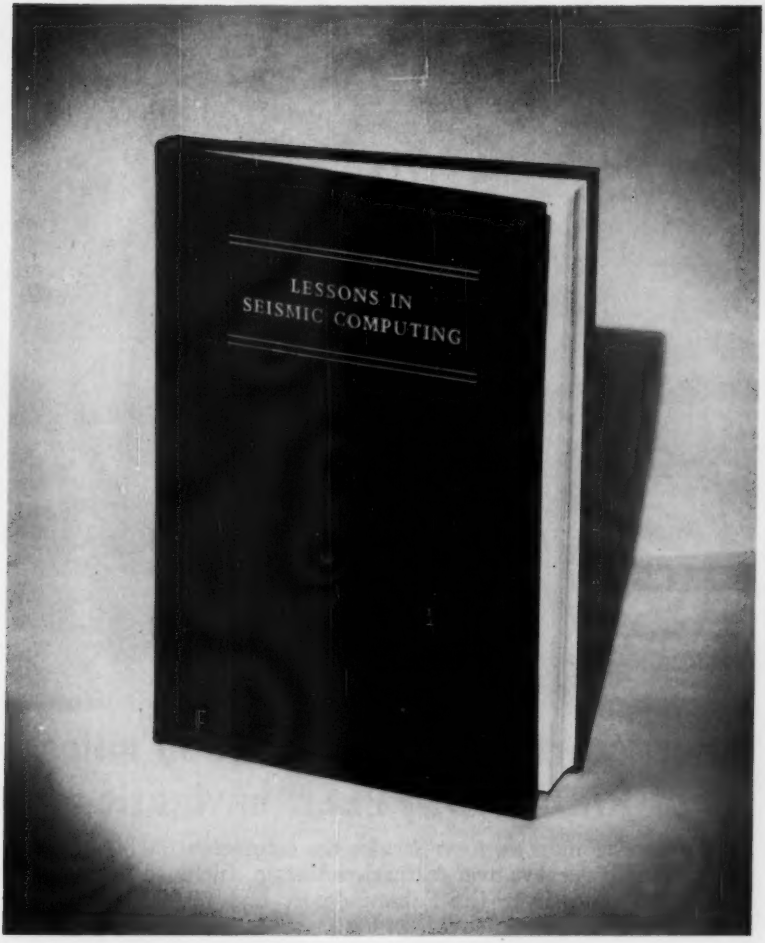

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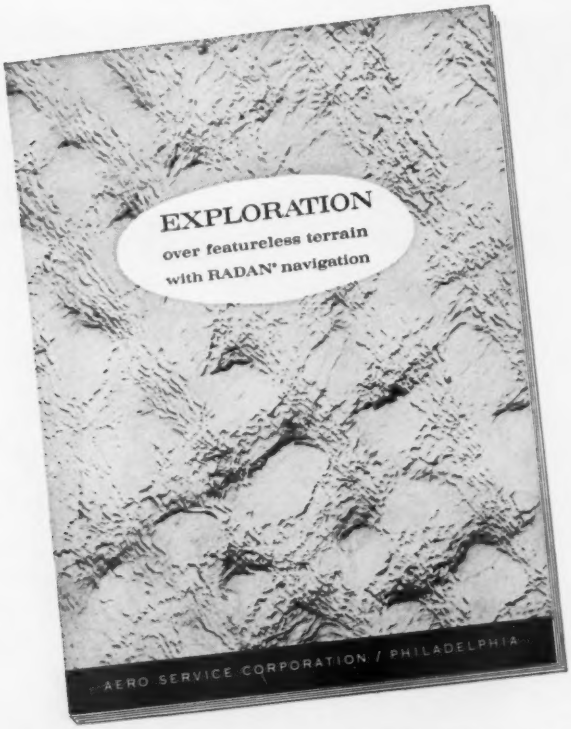

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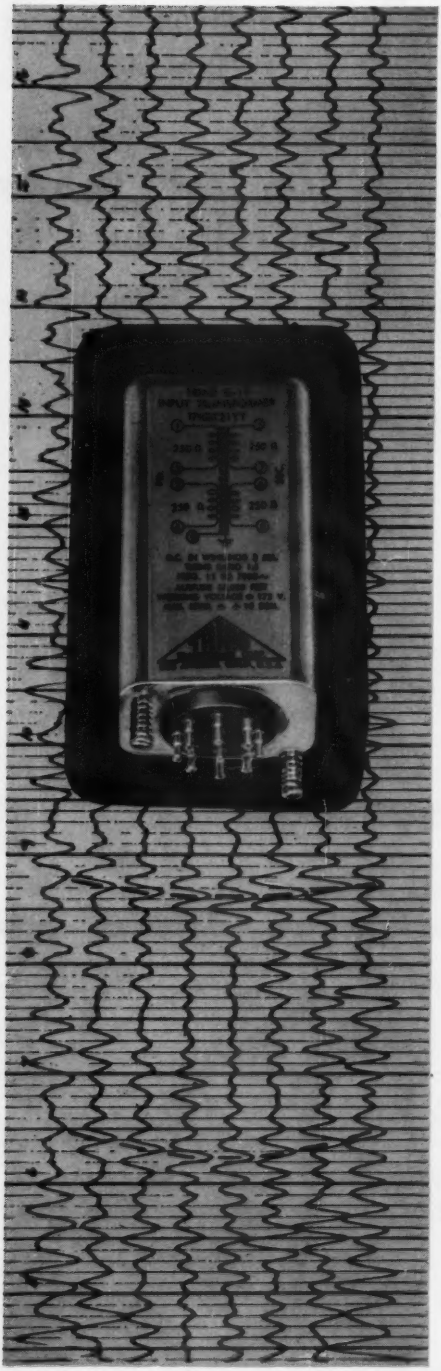

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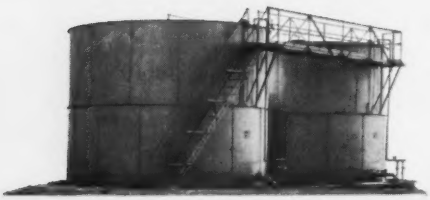

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(Continued from page 43)

sonnel safety. The "state of the art" in hermetic sealing has come a long way since then. In a comprehensive brochure on its specialty, **General Hermetic Sealing Corporation, Valley Stream, L.I., N.Y.** graphically portrays the company's modern techniques for researching, developing and producing hermetically sealed components and assemblies for industry and the military. Mr. William Brown, president, states that ". . . tests show that it would take over 30 years for less than a cc of air to penetrate a GHS sealed enclosure." In fact, it is claimed that a GHS hermetically sealed unit could outlast a similar, unsealed unit by more than 10 to 1 under the same environmental conditions. Featured in the presentation is the company's unique production line set-up for mass spectrometer leak testing, a bank of specialized instruments, and skilled operators that can gauge leak sensitivity to 10 to the minus 10th cc per second. GHS maintains a complete engineering service and self-contained production facilities to develop and produce single or volume quantities of components and assemblies, hermetically sealed against 7 major causes of product failure: humidity, altitude, fungus, salt spray, rain, explosive atmospheres, and dust. The GHS hermetic sealing brochure, which also includes a handy leak rate comparison table, is available on request by specifying Bulletin No. 426.

MAGACYCLERS

The new ES line of EXPANDED SCALE MAGACYCLERS—ultra precision frequency and pulse rate transducers—is

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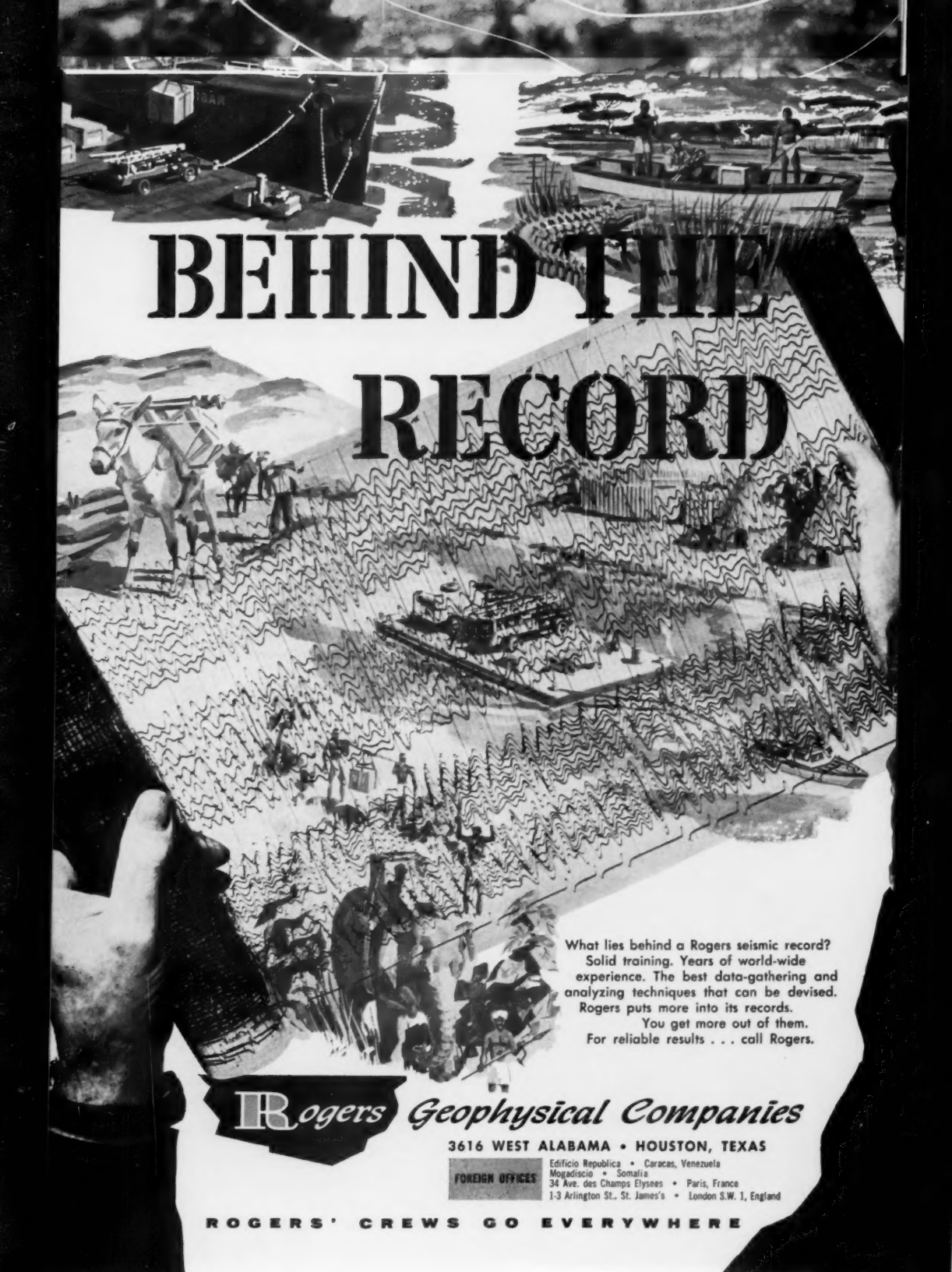
The Map-O-Graph, model MOGA, consists of a basic opaque projector, called

(Continued on page 63)



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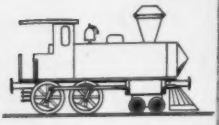

Mintrops Patent of Seismic Refraction Method

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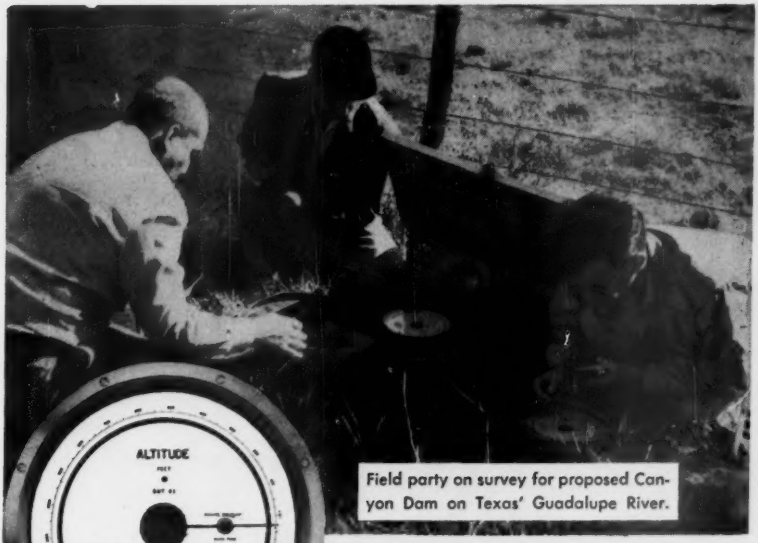

Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

TYPE FA-176

W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000′ up to max. limit of 5000′; **Accuracy** — 2.0′; **Sensitivity** — 0.5′; **Scale Length** — 20″; **Dial Size** — 8½″ dia.

For details on FA-176, send for Bulletin No. A-117.42

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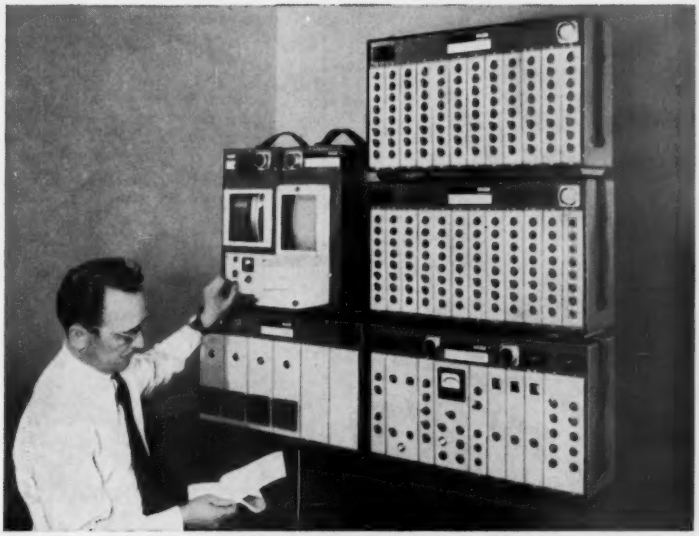

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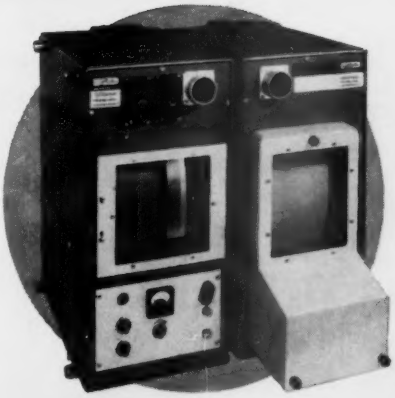

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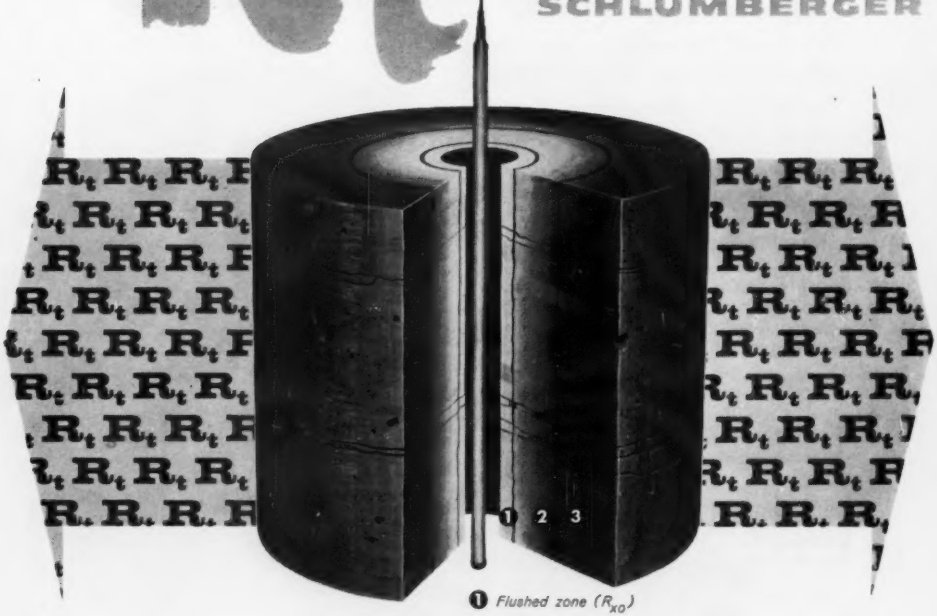

❶ *Flushed zone* (R_{xo})

❷ *Invaded zone* (R_i)

❸ *Undisturbed zone* (R_t)

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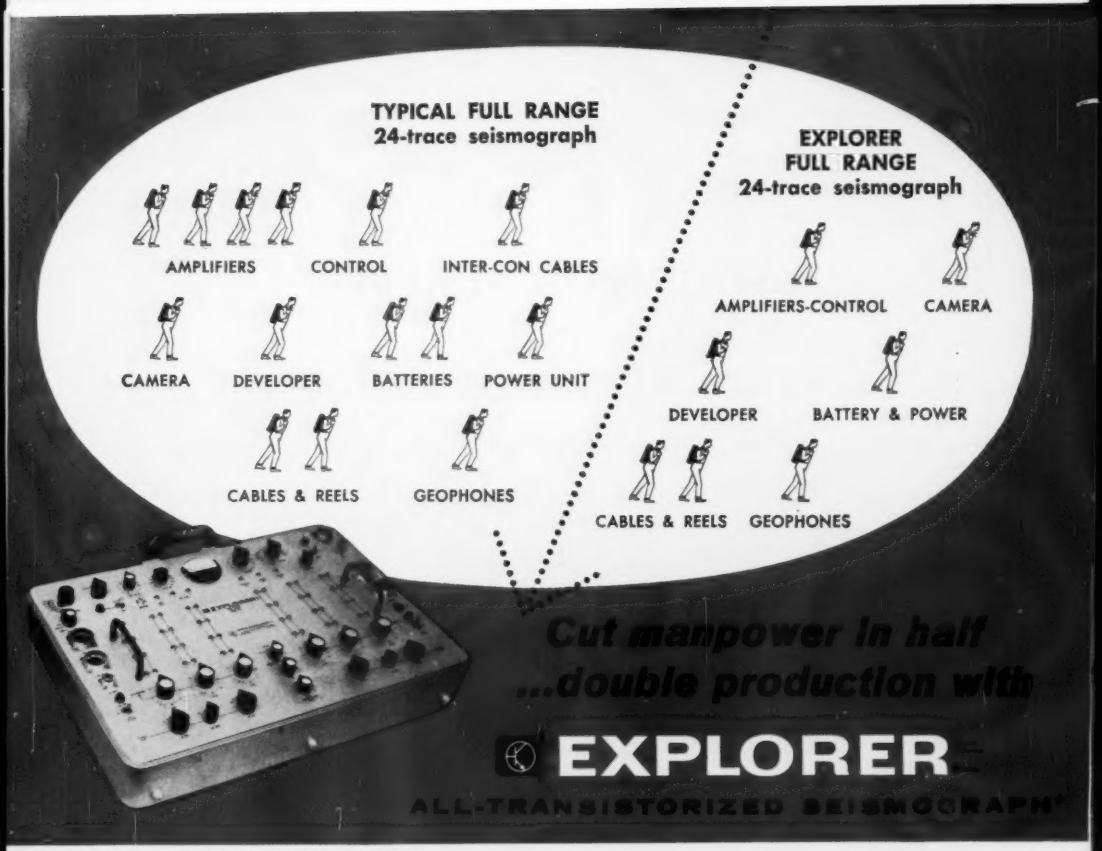

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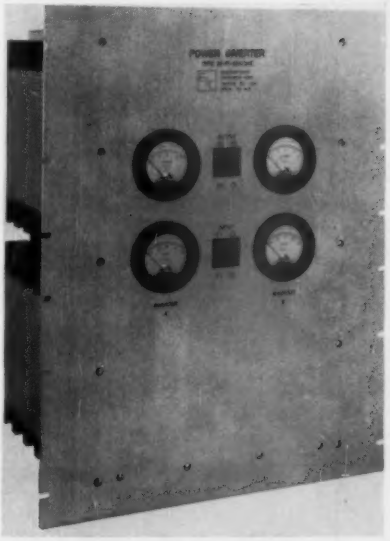
(Continued from page 53)

Art-O-Graph, which has enjoyed wide acceptance since 1949 in the graphic arts industries. Vertical in design, it ocupies no floor space, making use of overhead, "dead" space usually available.

Any roll map, opaque or transparent, up to the standard 54" width or larger, can be projected with the Map-O-Graph. The map is placed in a tray at the top, and the section to be projected is positioned over the 11" × 11" aperture by release of the pressure cover. A bottom tray holds the unwanted portion and the map can then be slid laterally or vertically, without releasing the cover, to change its position.

TRANSISTORIZED INVERTER

A new 2KW DC-AC inverter has been added to Electrodynamic Instrument Corporation's PI Series transistorized power supplies. The unit will supply a 2KVA output or two 1KVA outputs of 120 volts, 60 or 400 c.p.s. single phase, from an 11–14 v.d.c. or 22–32 v.d.c. source. Frequently stability of ±.01% and exceptional reliability make these inverters ideal replacements for troublesome and unstable rotary-type inverters in microwave, telemetry and automatic control installations. Efficiency at full load is about 85%. Solid-state circuit design throughout eliminates the need for standby power or warm-up



time. The standard rack panel unit measures 24½ × 19 × 12 in. **Electrodynamic Instrument Corporation, 2508 Tangley Road, Houston 5, Texas.**

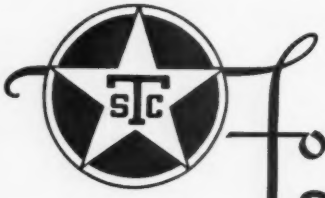
SEISMOMETER

The new National Type 19-L Seismometer, announced by **National Geophysical Company, Inc., 2345 W. Mockingbird Lane, Dallas, Texas,** combines unusually high sensitivity with exceptional ruggedness (no clamping of the suspension is

required at any time). The unit is available in any impedance from a few ohms up to 6,000 ohms. The natural frequency also can be varied from 3 to 10 cycles plus or minus .025 cycles.

The typical response curve for a 3.5 cycle unit, here illustrated, indicates this seismometer's excellent sensitivity. The 6,000-ohm load listed on the response curve is equivalent to a 15,000-ohm internal damping resistor and a 10,000-ohm input load. Combined with the National 26-A refraction unit, the 19-L Seismom-

(Continued on page 78)



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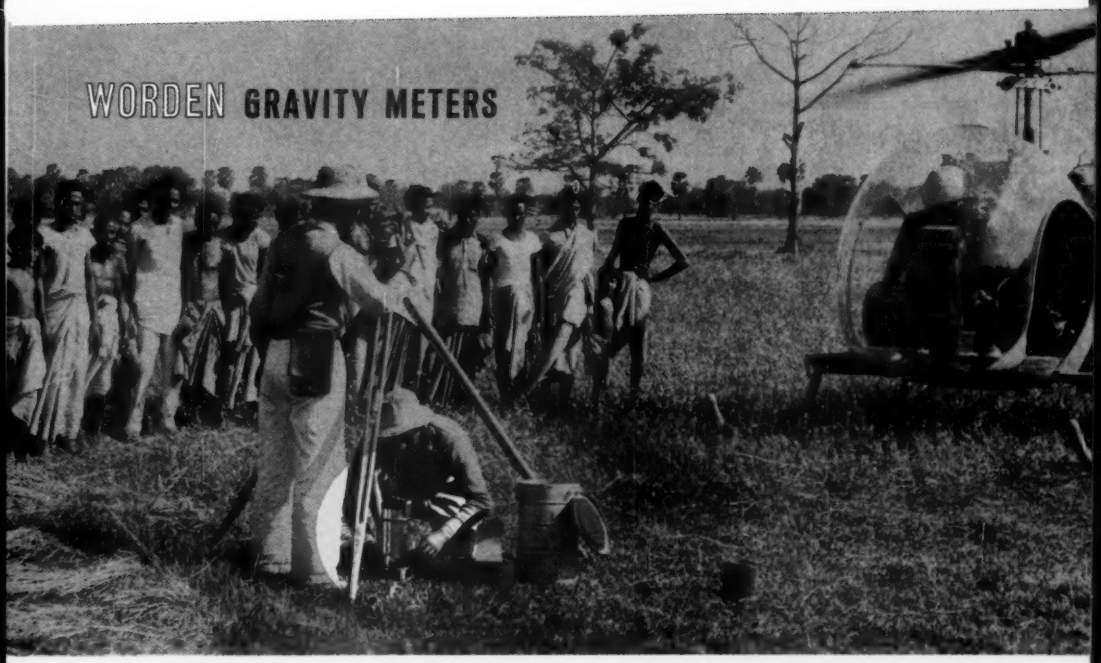

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Specifications for the respective *WORDEN* Gravity Meters are shown at right . . . contact TI's Gravity Department for additional information.

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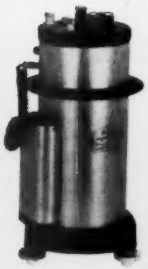

When requesting a quotation, copy the specification categories in this column and specify the values desired from those found under the respective meters.	the *Master*	the *Prospector*	the *Pioneer*	the *Educator*
Minimum Recommended Operating Range—Specify to nearest 100 mgls.* plus latitude and elevation indication	3000 mgls.	3000 mgls.	2400 mgls.	Limited . . . Will be at least 1600 mgls.
Minimum Total Operating Range (Reset) —Specify to nearest 100 mgls.*	5200 mgls.	5200 mgls.	4000 mgls.	Limited . . . Will be at least 2000 mgls.
Small Dial Range	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant (2200 on Special Order)	800 Dial Divisions x Small Dial Constant	800 Dial Divisions x Small Dial Constant
Small Dial Constant—Specify constant desired*	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	Standard .08 to .11 mgl./Dial Division (From 0.05-1.00 also available)	0.10-1.00 mgl./ Dial Division
Small Dial Calibration Linearity over full range	1 part in 1000	1 part in 1000	1 part in 1000	1 part in 1000
Small Dial Reading Accuracy	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division	0.1 of Small Dial Division
External Temperature Control	Temp. Stabilizer requires 1.00 watts power for a 100° F. differential. Four Rechargeable "D" Size Batteries maintain 90° F. differential for 10 hours and are mounted in removable pack on side of meter. Any 4.5 to 12 volt DC source may be substituted.	None	None	None
Small Dial Mechanism	Self counting, read from top and directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.		Side and top reading, directly coupled (no gears for backlash) with screw which contacts quartz measuring spring.	
Large Dial Range — Specify range desired*	800 Dial Divisions x Large Dial Constant			Geodetics not available
Large Dial Constant	Standard 6.5 to 12.0 mgls./D.D.			Geodetics not available
Large Dial Calibration over full range (8 turns)	Curve furnished with values accurate to one part in 1000—measured over full range (8 turns).			Geodetics not available
Size, Inches: Diameter Height	7" 14"	7" 14"	5½" 10½"	5½" 10½"
Weight, Pounds: Net Including carrying case	9¾ lbs. 18 lbs.	7½ lbs. 15¾ lbs.	5⅛ lbs. 12 lbs.	5⅛ lbs. 12 lbs.
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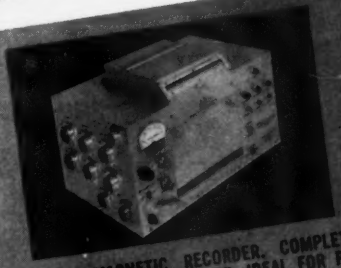

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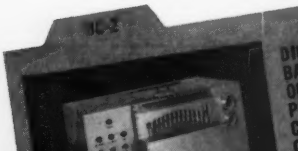

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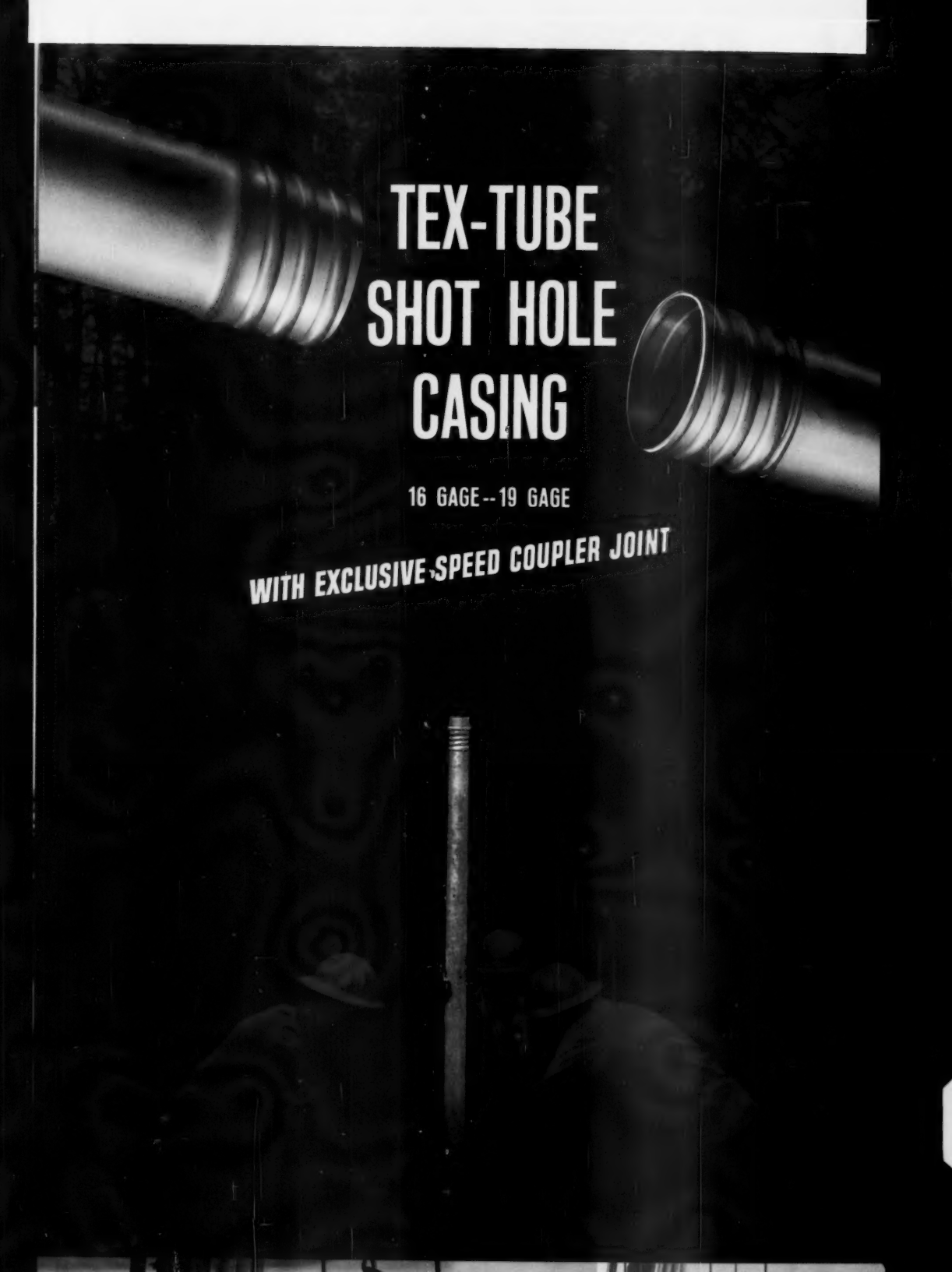
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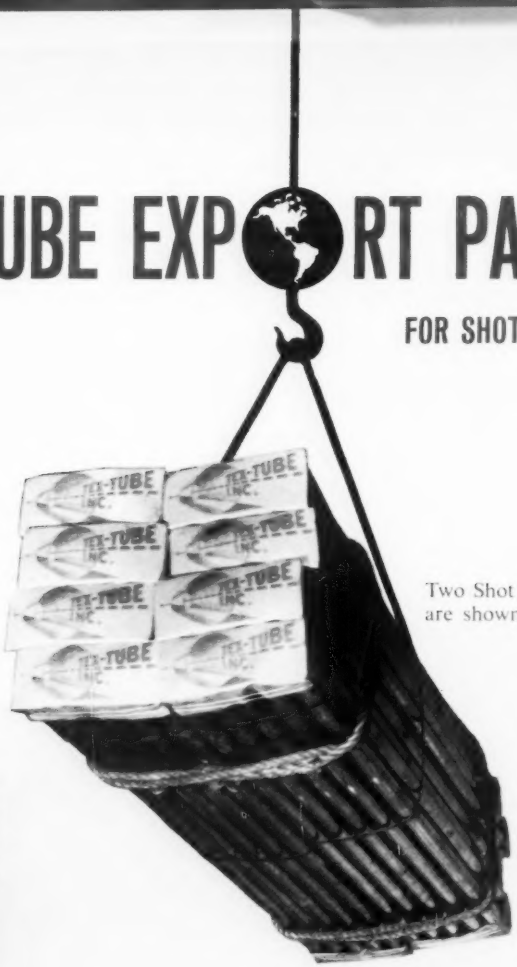

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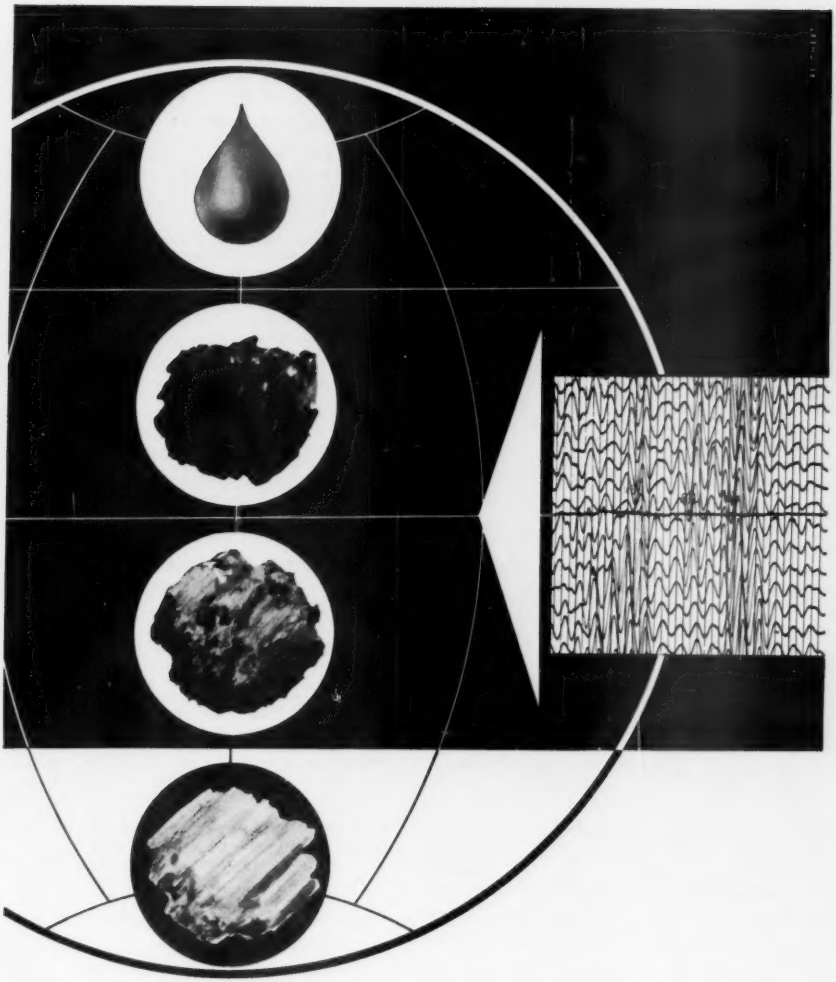

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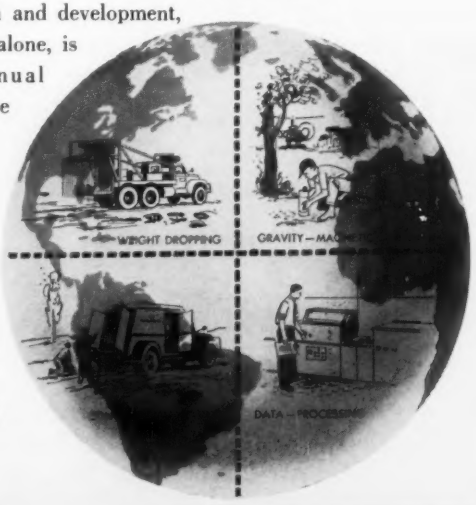

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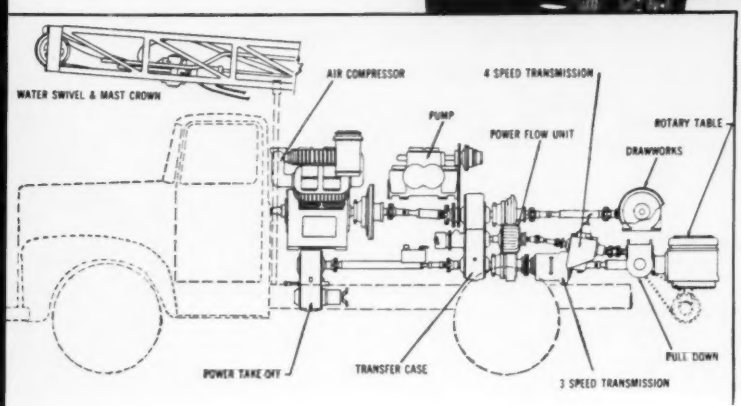

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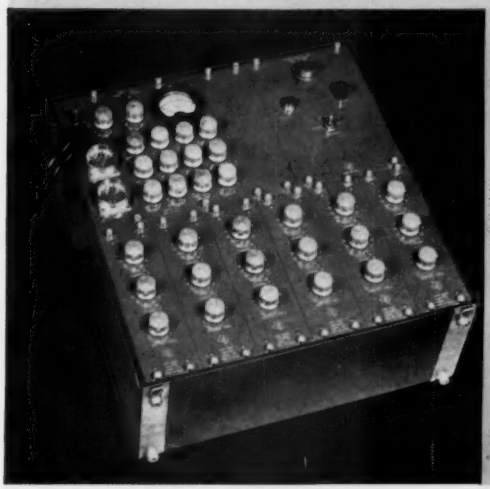

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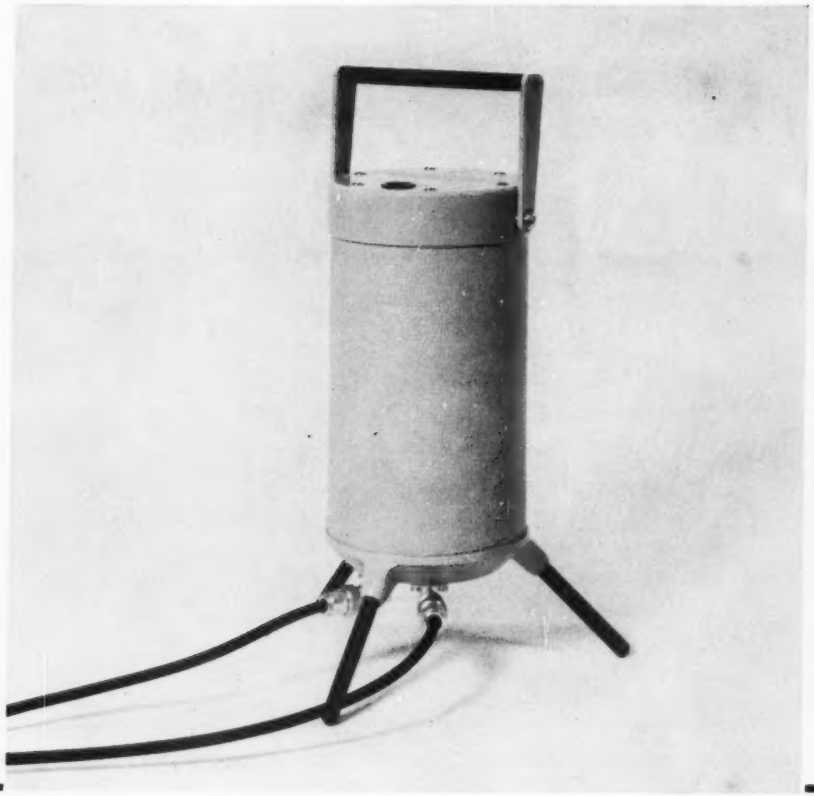

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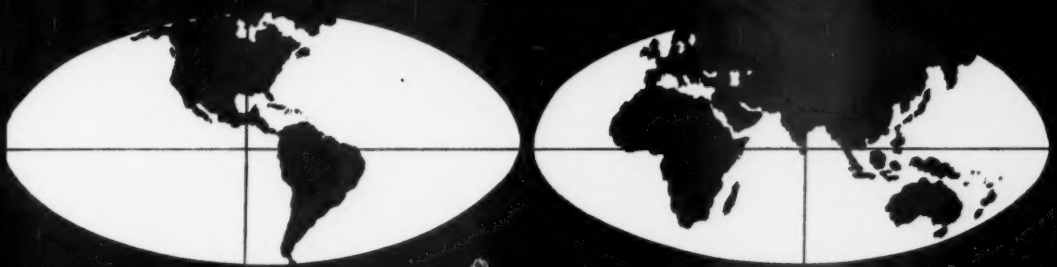

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